Jurnal Tribologi 42 (2024) 161-197

Jurnal Tribologi
Website : jurnaltribologi.mytribos.org e-issn: 2289-7232

Tribological evolution of ultra-high molecular weight polyethylene and its composites for hip and knee replacement implants: A review

Vipin Kumar, Ravi P. Tewari, Anubhav Rawat*

Department of Applied mechanics, Motilal Nehru National Institute of Technology Allahabad, INDIA.
*Corresponding author: manubhav-r@mnnit.ac.in

KEYWORDS

UHMWPE
Carbon nanotubes
Lubrication
Wear
Joint replacement implants
Micro-texture
Machine learning

ABSTRACT

The Ultra high molecular weight polyethylene (UHMWPE), a promising biomaterial in joint arthroplasty, has a semi crystalline form. UHMWPE has been used as bearing material in joint arthroplasty due to its superior resistance against wear, creep resistance, strength, bio inertness and low friction coefficient. However, the wear debris generated from this polymer cause serious problem as wear debris are biologically active and promotes macrophages induced osteolysis and implant loosening. Various attempts have been made by researchers to improve its wear resistance by reinforcing carbon fiber, carbon nanotubes, hydroxyapatite, graphene nano platelets and graphene oxides in polymer matrix over the years. Some of them also tried to improve wear resistance by surface texturing of alloys and ceramics. In this review the tribological properties of UHMWPE based composites, effect of lubrication and its concentration, and effect of micro texturing of hard surface have been presented.

Received 24 January 2024; received in revised form 12 March 2024; accepted 25 May 2024.
To cite this article: Kumar et al (2024). Tribological evolution of ultra-high molecular weight polyethylene and its composites for hip and knee replacement implants: A review. Jurnal Tribologi 42, pp.161-197.

1.0 INTRODUCTION

In total joint replacement surgery, a damaged joint is replaced with a prosthetic joint made of metal, ceramic, or plastic components (Affatato et al., 2012; Balagna, Spriano, & Faga, 2012). UHMWPE is often used as the bearing surface in these prosthetic joints (Oral & Muratoglu, 2015; Pramanik, Agarwal, & Rai, 2005; Uddin & Zhang, 2013), as it can withstand high loads and stresses that are applied on the joint during day to day human working. The UHMWPE has been used in total joint replacement surgery for years and has a proven track record of success (Hirakawa, Jacobs, Urban, & Saito, 2004; Kurtz, 2009; Wolford, Pitta, Reiche-Fischel, & Franco, 2003). It is biocompatible (Lapcikova et al., 2009; Patil, Njuguna, & Kandasubramanian, 2020; Reddy et al., 2018) and can be compression molded and machined into the desired shape and size for the use in a prosthetic joint (Wicaksono, Ismail, & Jamari, 2018). Additionally, the UHMWPE has a low coefficient of friction (Macuvele et al., 2019; Saikko, Morad, & Viitala, 2022), which helps in reducing the wear on the joint and improve its overall lifespan. The UHMWPE has been used in many orthopedic implants (Yang, Qu, Huang, Cai, & Zhou, 2012), including acetabular cups, tibial components, and femoral heads, and in spinal arthroplasties (Guedes, Kanagaraj, Sreekanth, Oliveira, & Fonseca, 2015; Ramakrishna, Mayer, Wintermantel, & Leong, 2001). The wear resistance, surface hardness and coefficient of friction are not the only properties which are required to be possessed by a material being used in a joint replacement implant (Kurtz, 2009). The total joint replacement implants are made up of metallic and polymer counterparts which have a motion relative to each other. This relative motion between the surfaces generates wear particles or debris, which promotes macrophage-induced inflammatory reactions and osteolytic tissue response (McGrath et al., 2001), activates the resorption of the bone surrounding the implant, and hence limits its life span and long-term use as a prosthesis (Brach del Prever, Bistolfi, Bracco, & Costa, 2009; Ingham & Fisher, 2005). The mechanism of macrophages to prosthesis wear debris has been shown in Figure 1. In addition, wear debris consideration, biocompatibility and cytotoxicity are also taken into consideration for successful implant (Salari, Mohseni Taromsari, Bagheri, & Faghihi Sani, 2019). The infiltrated and resident macrophages, neutrophils and fibroblasts are activated by the joint implants wear particulates at the implant site (Abu-Amer, Darwech, & Clohisy, 2007; Alhasan et al., 2022; Hodges, Sussman, & Stegemann, 2021; Mahon & Dunne, 2018). Neutrophils recognize biomaterials and form neutrophil extracellular traps (NETs) (Abaricia, Shah, & Olivares-Navarrete, 2021; Okeke et al., 2020; Selders, Fetz, Radic, & Bowlin, 2017). Fibroblasts and macrophages are involved in leukocyte recruitment at the prosthesis interface. The tumor necrosis factor (TNF-α) and IL-1 facilitate inflammatory response and combined with RANKL, can give rise to osteoclast precursor cells differentiation into activated bone-resorbing cells. These bone-resorbing cells lead to aseptic loosening of joint prosthesis as shown in Figure 1 (Couto et al., 2020; Mahon & Dunne, 2018; Santerre, Labow, & Boynton, 2000).

Thus, it becomes necessary to enhance wear resistance, increasing the life expectancy of biomedical implants. Over a period of time, several attempts have been made to enhance the wear performance of UHMWPE by reinforcement of carbon fiber (Ruan, Gao, Yang, & Yu, 2003; Thongruang, Balik, & Spontak, 2002), carbon nanotubes (CNT) (Xue, Wu, Jacobs, & Schädel, 2006), and graphene oxide (GO), and through crosslinking (Kilgour & Elfick, 2009; Schwartz, Bahadur, & Mallapragada, 2007; Stoller, Johnson, Popoola, Humphrey, & Blanchard, 2011; Wu, Zhang, Wu, Wang, & Jiang, 2013), and UV irradiation (Verma, Keshri, Zafar, Prasad, & Pathak, 2022a, 2022b; Verma, Pathak, Keshri, Prasad, & Zafar, 2022). Due to their resistance to heat and denaturation, bovine calf serum (BCS) (Fam, Kontopoulou, & Bryant, 2009; Kaddick & Wimmer, 2001; Liza, Haseeb, Masjuki, & Abbas, 2013) and alpha calf serum (ACS) (J-M Brandt, Charron, Zhao, MacDonald, & Medley, 2021; Jan-M Brandt, Charron, Zhao, MacDonald, & Medley, 2012; J. M. Brandt et al., 2010; Saikko, 2019; Saikko, Morad, & Viitala, 2021) are the most frequently used lubricants for tribological testing. Recent innovations involving the blending of vitamin E in UHMWPE demonstrate superior oxidative and wear resistance (Bracco & Oral, 2011; Fu, Doshi, Oral, & Muratoglu, 2013; Renò & Cannas, 2006). Several studies show that UHMWPE wear is influenced by the BCS protein concentration, type, and temperature (Saikko, 2003; Saikko et al., 2021).

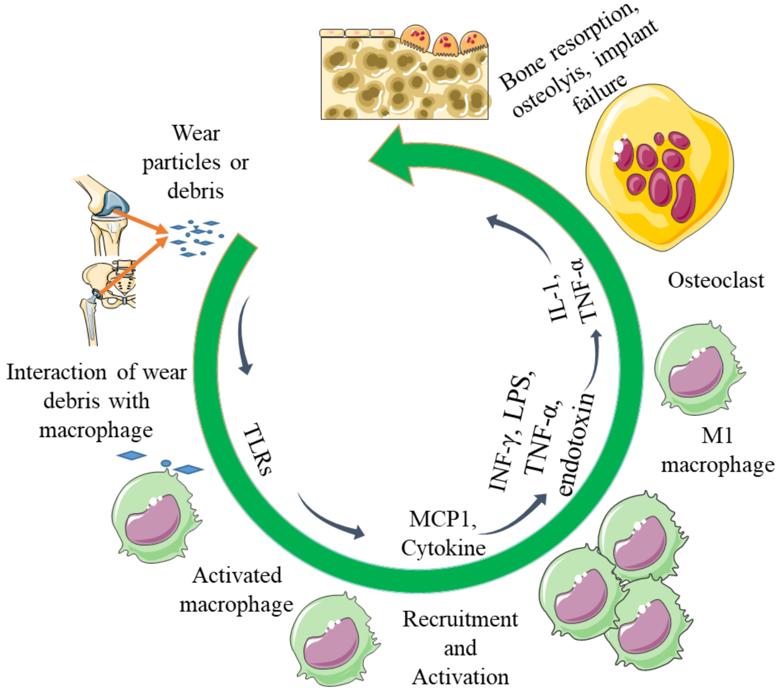


Figure 1: Illustration of periprosthetic osteolysis and aseptic implant loosening.

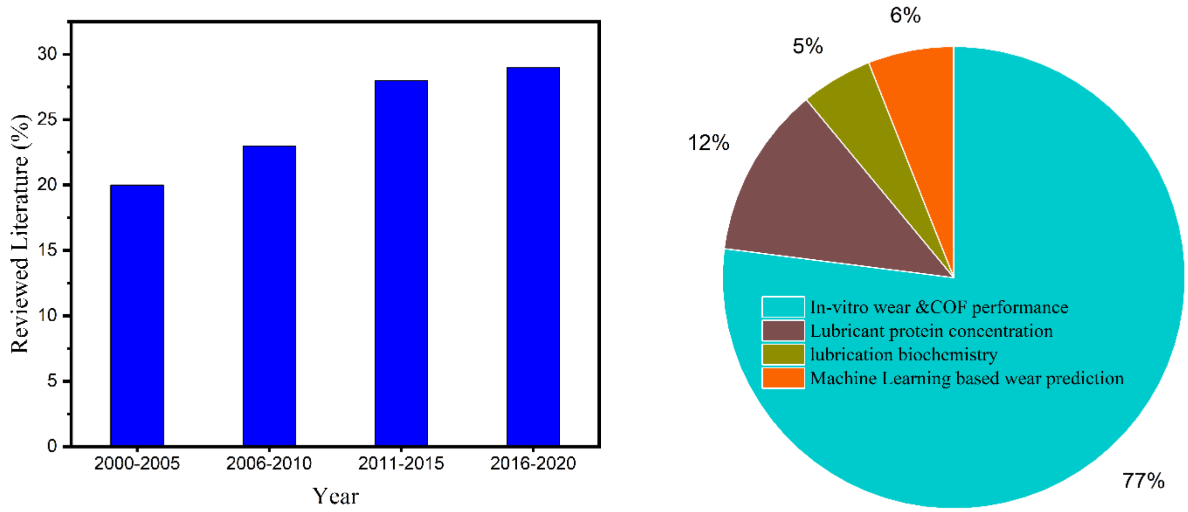
Apart from above in-vitro studies, machine learning could possibly be another modelling approach for designing and wear performance evaluation of polymer-based composites, as ML has successfully been applied in material engineering applications (Datta & Chattopadhyay, 2013; Mohanty, Bhattacharjee, & Datta, 2011; Vinoth, Dey, & Datta, 2021). In contrast to traditional parametric analysis, the development of data-driven artificial intelligence (AI) and machine learning (ML) algorithms have allowed to explore complex higher-order correlations among multiple parameters on a broader range. Advanced ML models, such as the Gradient Boosting Machine (GBM) (B. Liu, Vu-Bac, Zhuang, Fu, & Rabczuk, 2022), K-Nearest Neighbor, Random Forest (Borjali, Monson, & Raeymaekers, 2019), and Artificial Neural Network (ANN) (Huber & Tsakmakis, 2001; Malinov, Sha, & McKeown, 2001), make use of sophisticated algorithms to find multiplex trends in the dataset and predict the output accurately. These have been successfully used to predict the wear and friction characteristics of aluminum alloys, aluminum-graphite MMCs, and total hip replacement implants from tribological test conditions (Hasan, Kordijazi, Rohatgi, & Nosonovsky, 2021, 2022a, 2022b, 2022c; Hasan & Nosonovsky, 2021). ML algorithms have also been used for classification of progressive wear and evaluation of biomechanical responses in acetabulum of the hip joint (Deshpande et al., 2024; Haribabu & Basu, 2024).

The wear of UHMWPE in total hip replacement application depends upon various factors, including the content of reinforcing material, viz. Carbon fiber, carbon nanotube, graphene, hydroxyapatite, and lubricant properties. Graphene has excellent mechanical and wear properties, but its biocompatibility and response to biological tissue still need clarification. Reinforcement of hydroxyapatite in UHMWPE reduces wear only if it is added in high amounts. There is a need for research to identify the type of lubricant, lubricant protein concentration, and operating temperature for hip replacement implants to get realistic wear as seen in vivo. The main problem with lubricants is their protein denaturation, and it is still a matter of concern which type of protein is denaturing, viz. albumin, globulin, and others. Several advancements in UHMWPE have been carried out to increase wear resistance for knee replacement applications. The researchers have tried to reduce wear and oxidation by crosslinking and vitamin E supplementing. The crosslinking enhances the wear resistance, but it reduces the mechanical properties. The crosslinking of UHMWPE produces a smaller size of wear particulate, and they are more biologically active and hence cause osteolysis-induced implant loosening.

The current review discusses various methods for enhancing the wear performance of UHMWPE, including reinforcement with carbon fiber, carbon nanotubes, graphene oxide, hydroxyapatite and micro texturing of countersurface for total hip and knee replacement applications. The significance of the type of lubricants, their protein concentration, and operating temperature in joint replacement implants tribological testing have also been discussed. It also discusses the potential application of machine learning for designing and evaluating wear performance in UHMWPE-based composites, citing successful ML applications while evaluating the wear performance of total hip and knee replacement implants.

2.0 MATERIALS AND METHODS

The material in this review is based on published research articles and product information in order to cover all phases from early-stage research to products in clinical use. The database is searched from 2000 to 2023, and the research articles were found in the literature database with the primary focus on "UHMWPE, wear," "UHMWPE, Carbon nanotubes, CNT joint replacement implant, wear," "UHMWPE, Graphene/ graphene oxide and or hydroxyapatite, joint replacement implant, wear" and "UHMWPE, HA, wear, surface modification, and biocompatibility." The summary of investigated research has been shown in Figure 2. The majority of the literature is found between 2000 and 2023 and there has been a recent surge in research activity and interest in the subject, and advancements in the field are becoming more prominent. The current state of the art covers various types of research work, including experimental studies and Machine Learning base studies for tribological evaluation of UHMWPE-based composites for total joint replacement applications. As can be seen from Figure 2 (b), from the total literature reviewed, 77% of studies have evaluated in-vitro wear and COF, 12% of studies have centered on the type of lubricant and its protein concentration, 6% of studies have applied ML algorithms in order to access tribological performance of these joint implants.



(a) (b)

Figure 2: Graphical illustration of (a) year wise percentage of reviewed literature (b) objectives of the reviewed literature.

3.0 ROOT CAUSES OF IMPLANT FAILURE

The prevention of premature failure of orthopedic hip implants is a constant challenge for physicians and engineers (Buford & Goswami, 2004). The fact that 7 million Americans already rely on hip or knee replacements speaks volumes about the substantial influence these surgeries have on public health (Kremers et al., 2015). It is required to know exact mode of failure for hip and knee replacement implants for more accurate design and development of materials for total hip and knee replacement application. Sadoghi et al. (Sadoghi et al., 2013) identified possible causes of joint prosthesis failure, and thus revised prosthesis with the help of several joint registries across the world, including New Zealand, Denmark, Sweden, Norway, and Finland. It is found that implant loosening (Gallo, Vaculova, Goodman, Konttinen, & Thyssen, 2014; Goodman et al., 2003; Hodges et al., 2021; Steinbeck, Jablonowski, Parvizi, & Freeman, 2014; Sundfeldt, V Carlsson, B Johansson, Thomsen, & Gretzer, 2006) is a most common reason for prosthesis failure in total hip replacement (THA) (55.5%) and total knee replacement (TKA) (29.8%). The instability (Luttjeboer, Bénard, Defoort, van Hellemondt, & Wymenga, 2016; Naudie & Rorabeck, 2004; Rodriguez-Merchan, 2011) and septic loosening (Pajarinen et al., 2010; Weeden & Schmidt, 2007; Zhang et al., 2012) also require prosthesis revision but less severe than wear debris-induced aseptic loosening. The graphical representation of all possible causes for the revision of prosthesis has been shown in Figure 3.

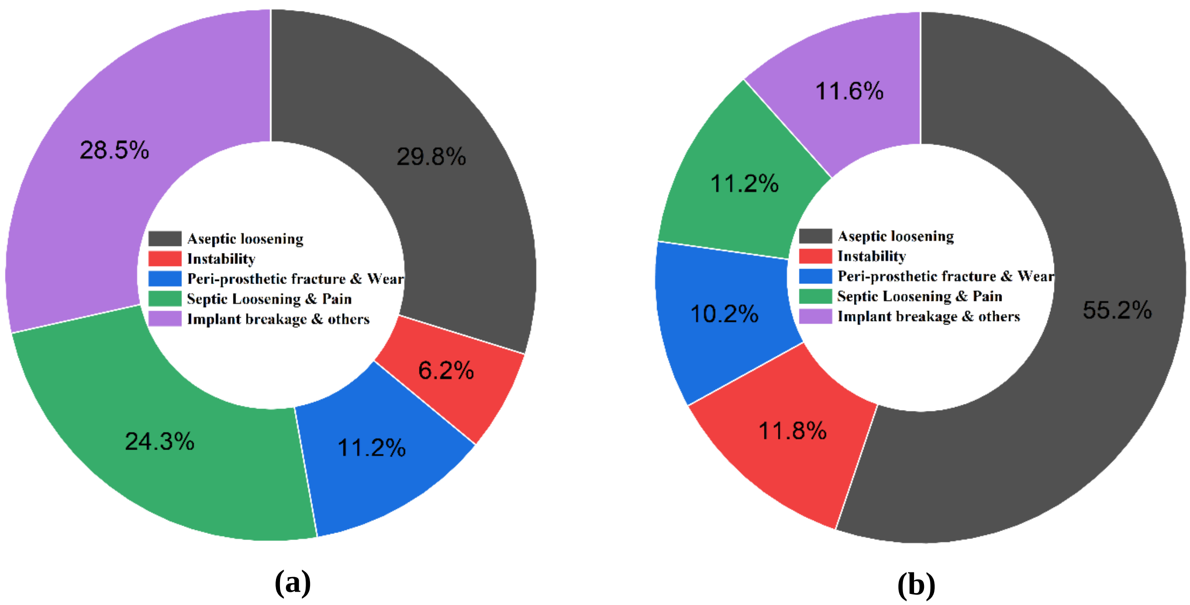


Figure 3: Illustration of possible root causes for revision after (a) TKA and (b) THA (Sadoghi et al., 2013).

It is evident from Figure 3 that implant loosening is the primary cause of its failure. This implants loosening is result of gradual wear of UHMWPE inserts over the period of time. Thus, more wear-resistant implant designs are required as the demand for hip implantation rises, particularly as younger, more active patients are having hip and knee prosthesis placed. The wear at articulating contact sites caused by current hip prosthesis designs emphasises the need for research into factors influencing wear rates for implants with longer lifespans.

4.0 WEARING OF TOTAL JOINT REPLACEMENT IMPLANTS

Wear in total joint replacement implants is a very complex phenomenon to explain which happens at the interface of articulating surfaces and leads to loss of material in the form of wear debris from the articulating surface. The aseptic loosening induced by wear debris of UHMWPE is considered as a primary cause of the shorter lifespan of total joint replacement implants (Figure 3) (Koerten, Onderwater, Koerten, Bernoski, & Nelissen, 2001). The wear mechanism in total joint replacement implants are defined as per their nature to remove the material from the bearing surface (Affatato, 2012). The Wear phenomenon may be a significant concern in joint replacement implants, such as total hip replacements and total knee replacements as it may lead to the degradation of the implant over time and potentially cause it to fail. There are mainly three types of mechanisms which may cause above wear namely; abrasion, adhesion, and fatigue, which are encountered over a period of time (Shen, Fang, & Kang, 2018), and have been shown in Figure 4.

4.1 Abrasive Wear

The abrasive wear came into existence when a hard rough surface has a relative motion against the comparatively soft counter face and generates bioactive wear asperities by abrasion (Affatato, 2012). The material removal from the soft surface has happened due to the cutting and ploughing action of wear particles which act as a cutting tool between the surfaces (McKellop, 2007). The ceramic fragments embedded in polyethylene acetabular cups which promotes third body abrasive wear in acetabular cup, can be seen in the Fig 4 (a). Figure 4 (a) shows polyethylene third body wear with embedded ceramic fragments in an acetabular cup and tibial insert for THA and TKA respectively. The wear particles, which were left inside during the surgery, were commonly known as third body particles and have the potential to initiate wear phenomenon after surgery by rubbing action at bearing counter surfaces (Fabry, Zietz, Dammer, & Bader, 2015; McKellop & D'Lima, 2008).

4.2 Adhesive Wear

Adhesive wear is a type of wear that occurs when two surfaces come into contact and experience relative motion, causing one or both surfaces to become damaged or worn away due to the adhesion or bonding between the surfaces as shown in Figure 4 (b) (Myshkin, Petrokovets, & Kovalev, 2005). Artificial joints are often subject to adhesion as a wear mechanism because of high contact stresses between the bearing surfaces. Adhesive wear is often caused by the transfer of material from one surface to the other, as well as by the shear forces that are generated between the two surfaces. Stewart et al. (Stewart, 2010) reported that joint prosthesis is subjected to a load that has a three times magnitude than that of an individual's body weight. Due to this high load, the contacting surfaces get fused and would result in the transfer of soft material onto hard metal surfaces (Shen et al., 2018; Wilches, Uribe, & Toro, 2008).

4.3 Fatigue Wear

Fatigue wear is caused primarily by cyclic loading at the articulating surface, which starts cracks and spreads them to cause delamination and pitting damage over time. The representation of fatigue wear is shown in Figure 4 (c). A study by Ansari et al. (Ansari, Ries, & Pruitt, 2016) found that cyclic motion may cause micro-cracks to develop in knee joint replacement implants, causing a fractures.

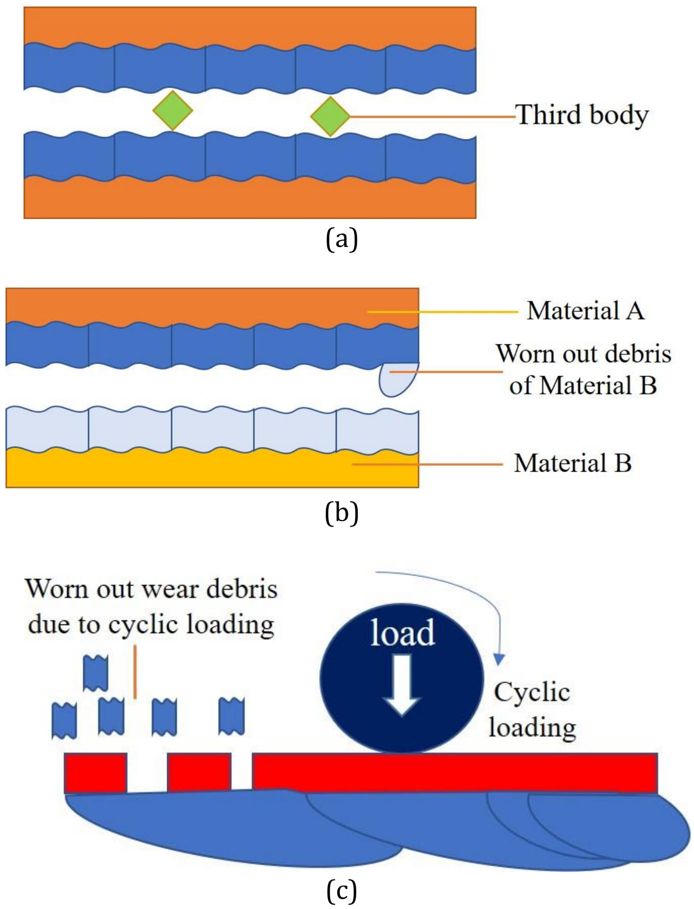


Figure 4: Schematics diagram of wear mechanism commonly seen in human joint replacement implants (a) third body abrasive wear (b) adhesive wear (c) fatigue wear.

5.0 HISTORICAL EVOLUTION OF UHMWPE IN THE AREA OF JOINT REPLACEMENT IMPLANTS

The history of the UHMWPE orthopaedic applications spans over 60 years, and its evolution has been a result of the many innovations that have occurred in the field. The early days of the UHMWPE were focused on its use as an experimental material for joint replacement. However, it was not until the late 1970s that UHMWPE began to be used more extensively as a replacement for existing materials. The UHMWPE was first introduced by Sir John Charnley in November 1962 (Sharma, Chowdhury, Keshavan, & Basu, 2023). Since its introduction, the UHMWPE has played a crucial role in joint replacement over the last forty years, which is a remarkable milestone in the field of orthopaedics. Several advancements have been done in the UHMWPE, to improve its resistance against wear, and mechanical and biological characteristics. In the 1970s, with the reinforcement of carbon-fibre (CFR), in the UHMWPE materials researchers attempted to improve the wear resistance of the UHMWPE for orthopaedic applications. In contrast to the Charnley's conventional UHMWPE (Kurtz, Muratoglu, Evans, & Edidin, 1999), this CFR reinforced composite did not show consistent or better clinical outcomes. Whereas, at the same time a highly crosslinked UHMWPE, is introduced by the researchers of Japan and South Africa having irradiation dose of 1000 KGy in air and 700 KGy in acetylene respectively (Grobbelaar, Du Plessis, & Marais, 1978; Oonishi, 1995). The Thackray Ltd., Leeds based company, began developing HDPE, injection molded with silane chemistry in the 1980s (Kurtz, 2016). In the late 1980s, a joint venture between DePuy Orthopedics and DuPont created a highly crystalline form of UHMWPE known as Hylamer, but this polymer also doesn't have satisfactory clinical performance. In view of these shortcomings of the UHMWPE, the development of the first and second generations of highly crosslinked UHMWPE began in the 1990s and 2000s (Kurtz, 2016). However, the UHMWPE developed by Charnley continues to be the benchmark for artificial hips and other joints, such as the knee and the shoulder. Figure 5 shows the historical development of the UHMWPE as a bearing material for the joint prosthesis. The tribological performance of UHMWPE and its composites is summarized in Table 1.

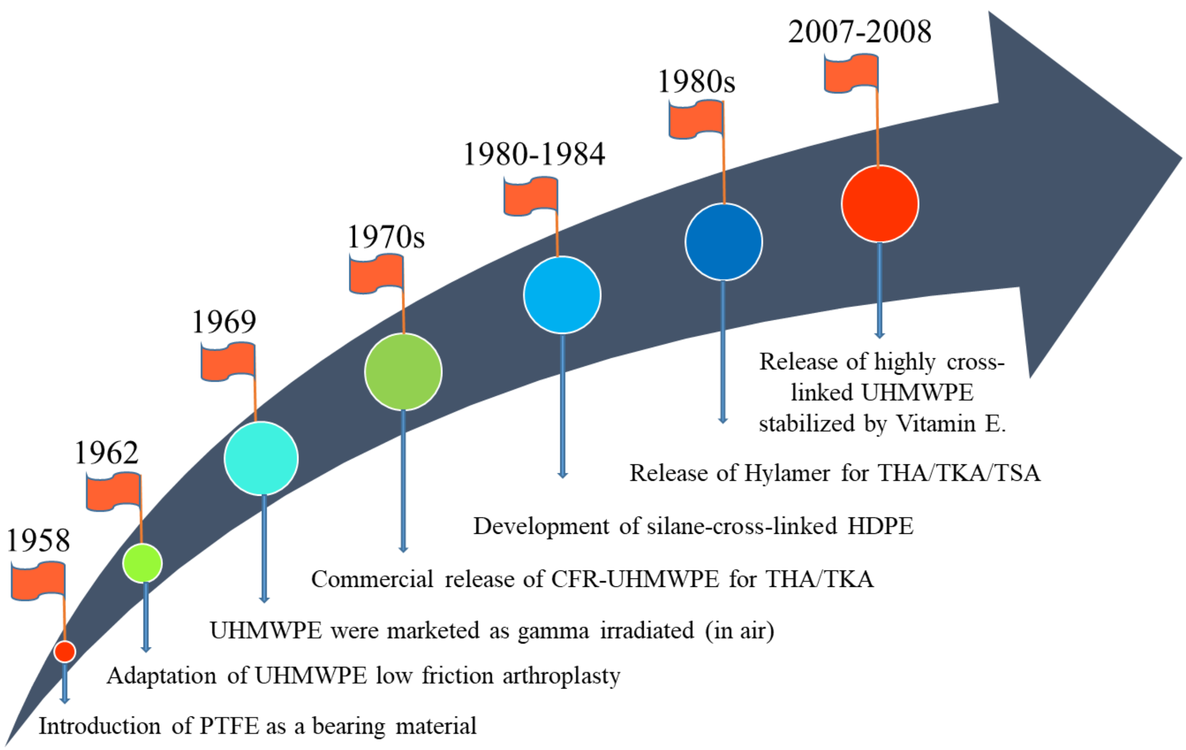


Figure 5: Historical evolution of UHMWPE and its composites in the field of arthroplasties.

6.0 ENHANCING TRIBOLOGICAL PROPERTIES OF UHMWPE

It has been a tradition for the researchers and engineers to improve the wear performance of materials by reinforcing various suitable materials to them. In that context Carbon fibre (Chukov et al., 2015), Carbon nanotubes (Silvia Suñer, Bladen, Gowland, Tipper, & Emami, 2014), Graphene nanoplatelets/oxide (Chen et al., 2012; Lahiri et al., 2014) and Hydroxyapatite (J.-L. Liu, Zhu, Wang, & Ge, 2008) etc., as explained in subsequent sub- sections are few of those important one.

6.1 Effect of Carbon Fiber-UHMWPE Composite on Wear Performance of Joint Implants

Carbon fibre (CF) has excellent tensile strength and elastic modulus, and the addition of CF in a polymer matrix can significantly improve its tribological and thermal characteristics (Chukov et al., 2015; Dangsheng, 2005; Rezaei, Yunus, & Ibrahim, 2009; J. Wang, Chen, Liu, Han, & Yan, 2014). Chukov et al. (Chukov et al., 2015) experimentally investigated the effect of CF induced surface amendment and its interaction at a fiber-matrix interface in the UHMWPE composites. They found an improved interfacial interaction between UHMWPE and CF by air induced thermal oxidation at 500°C, and composites formed by this process show elevated tribological characteristics. The surface modification CF was by chemical and thermal oxidation, and in chemical oxidation by the action of HNO3 at 250C followed by washing and drying. The milling and compression moulding were done in the view of mixing GUR 4120 UHMWPE powder and CF (0-12wt %), and preparing composites (Chukov et al., 2015). Distilled water was used as a lubricant medium, and a Pin-on-disc tribometer was used for further tribological assessment of respective composites. It was observed that the wear rate was significantly reduced by the addition of CF in UHMWPE polymer, and minimum wear of magnitude 110 μm is found at 8wt% of CF. This reduced wear of CF-UHMWPE composite was possible due to the change of wear mechanism from adhesion to fatigue wear (Cao, Liu, Ge, & Wu, 2011). Dangsheng (Dangsheng, 2005) also investigated the effect of CF content on tribological and mechanical characteristics and used MM-200 tester to evaluate the wear performance of the CF-UHMWPE composite. The volumetric wear loss was found to be reduced against the addition of CF in polymer and wear is reduced faster at 0-20% CF as compared to 20-30% CF content in the polymer matrix. The lowest wear was observed at 8 wt% CF, and it was twofold lower as compared to pure UHMWPE. Adding CF into UHMWPE increases the hardness of the composite, making the friction coefficient more stable, and an abrasive wear mechanism comes into existence. The worn surfaces had not shown any surface undulation as seen in pure UHMWPE. The sample preparation method also played a crucial role in the tribological performance of the CF-UHMWPE composite. The ball-milled samples showed a more uniform distribution of CF within the matrix material. The graphical representation of variation of wear volume with rise in carbon fiber content is shown is shown in Figure 6.

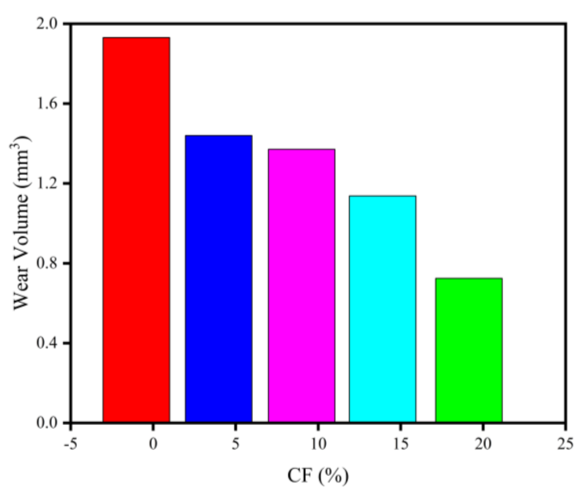


Figure 6: Schematic diagram depiction volume loss due to wear on increasing the content of carbon fiber under dry condition (Dangsheng, 2005).

6.2 Effect of Carbon Nanotubes-UHMWPE Composite on Wear Performance Of Joint Implants

Carbon nanotube (CNT) and UHMWPE can be combined to form composite materials that combine the unique properties of both materials. Reinforcement of CNTs to UHMWPE improves the strength and conductivity of the material while maintaining its biocompatibility and low-friction properties. These composites have potential applications in the field of biomaterials and medical devices, such as in tissue engineering and drug delivery systems.

The CNT/UHMWPE composites were prepared by means of blending the CNT and UHMWPE powder. After the blending, hot pressing was performed in order to fabricate the composites, and a few studies have prepared a composite film on a steel substrate using the dip coating technique. In general, Multi Walled Carbon Nanotubes (MWCNT)were obtained by catalytic decomposition of C2H2 chemical vapor decomposition. It was also reported that only a few studies have worked on Single Walled Carbon Nanotubes (SWCNT) (Y. Liu & Sinha, 2013; Samad & Sinha, 2011). The improved mechanical and wear properties of composites were ensured by proper adhesion of CNT to the polymer matrix and proper interfacial bonding was obtained by acid and plasma functionalization technique. Suñer et al. (Silvia Suñer et al., 2014) used a pin-on-plate wear tester to assess the tribological performance of virgin and CNT reinforce UHMWPE. The counter surface is made of cobalt chromium against which composite pins were sliding. They found that wear factor was highest for Pure UHMWPE and found to decrease with an increase in wt% of CNTs in bulk UHMWPE. Authors also found a 30% reduction in wear rate in the case of 0.5wt% CNT/UHMWPE sample and no significant difference in wear rate between 0.5wt% CNT and 1wt% CNT was observed. The addition of a higher concentration of MWCNTs did not show a significant effect on the wear rate (B. B. Johnson, Santare, Novotny, & Advani, 2009; Xue et al., 2006). Zoo et al. (Zoo, An, Lim, & Lim, 2004) also reported similar results consistent with Suñer et al. (Silvia Suñer et al., 2014) .They reported significant improvement at 0.5wt%CNT. Yousef et al. (Yousef, Visco, Galtieri, Nocita, & Espro, 2017) investigated the effect of CNT and paraffin oil addition to the bulk UHMWPE on wear rate by means of pin-on-disk Tribometer in air, artificial and natural lubricating medium. The artificial lubricant was prepared by dissolving 0.3% hyaluronic acid in phosphate buffer saline solution and the natural lubricant consists of bovine serum. In the wear analysis, test specimens were prepared by mixing through ball milling and ram extrusion process, and further, they were compression moulded as per protocol given by Suarez et al. (Suarez & de Biasi, 2003). It was concluded from the investigation that ball milled samples show elevated wear resistance as compared to twin screw extruded samples for 1wt% carbon nanofiller in a natural lubricant medium. The ball milled samples at 1wt% carbon nanofiller have shown 75.5% improvement in wear resistance as compared to pure UHMWPE/2wt% paraffin oil samples. This behavior of ball milled samples was due to the fact that the ball milling mixing produces more ductile nanocomposites than extrusion mixing (Visco et al., 2016). The abrasive wear mechanism involves material loss from the composites' surface (Yousef et al., 2017). Kumar et al. (Kumar et al., 2019) worked on modifying the CNT/UHMWPE composite surface using solvent based etching and lyophilization techniques. They proposed gentamicin-loaded chitosan impregnation on porous surfaces resulting from the etchant's action. It was concluded that specific wear resistance is reduced by 20% compared to the pure UHMWPE. The impregnated chitosan acts like a lubricating agent, which helps in lowering the coefficient of friction; thus, improved wear resistance was obtained. The crystallinity of the composite was also a critical factor in determining the wear resistance of composites. The crystalline phase of composites shows satisfactory fatigue and damping properties while dissipating contact loads (Colaco, Gispert, Serro, & Saramago, 2007), thus showing good energy dissipation and reduced wear rate in composites (Fang et al., 2015; Kumar et al., 2019). A detailed comparison of wear rate between CNT-UHMWPE and pure UHMWPE has been presented in Figure 7.

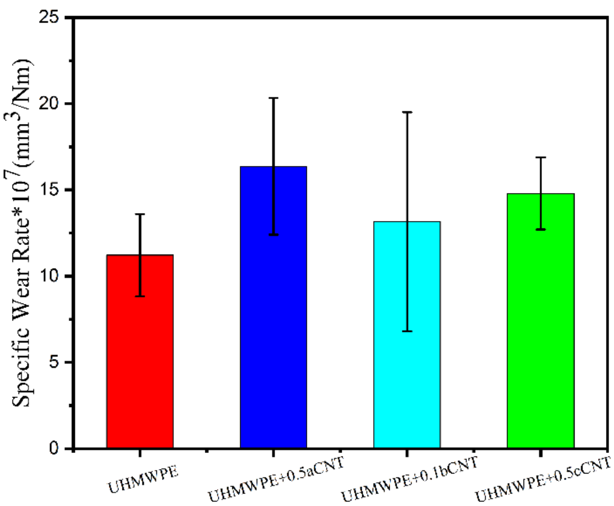


Figure 7: Schematic diagram showing wear rate of UHMWPE composites reinforced with CNT (Y. Liu & Sinha, 2013).

The studies revealed that wear factors, wear loss, and wear depth of CNT-UHMWPE decrease by 20% to 80% compared to pure UHMWPE. As CNT concentration increases, wear resistance and wear life improve more pronouncedly. Samad and Sinha (Samad & Sinha, 2011) reported that the composite exhibited a 300% increase in its cycles without failure when only 0.2 wt% of CNTs were added.

These studies have delved into the wear characteristics of the CNT-UHMWPE composite. However, it is important to note that most of these studies have not used situations representative of clinical scenarios. In order to increase the wear resistance of CNT-UHMWPE composites, gamma or electron beam irradiation should be employed. It becomes necessary to conduct additional tribological tests under cross-shear conditions that mimic human joint motions.

Table 1: Description of the CNTs/UHMWPE composites wear rate.

Authors	**Material/Testing Method**	**Test conditions**	**Wear**	**Wear Mechanism**
M. Abdul Samad and Sujeet K. Sinha (Samad & Sinha, 2011)	UHMWPE+SWCNT (0.05-0.2wt %) Ball-on-disk wear test Ball: silicon nitride Ball Dia: 4mm	Load: 4 N Speed Range: 1000-2500 rpm Ra = 5 nm	Wear life increased in range of (150%-310%)	-

S. Suñer et al. (Silvia Suñer et al., 2014)	Bulk: UHMWPE (GUR 1020) + CNT (0.5-1wt %) Pin-on-plate wear test Plate: CoCr	Load: 160 N stroke length: 28mm Frequency:1 Hz Ra=0.01 µm	Reduction of wear rate by 30% at 0.5wt% MWCNT and showing no significant further improvement at 1wt% MWCNT.	-
Liu and Sinha (Y. Liu & Sinha, 2013)	UHMWPE(GUR143)+ (0.5wt%MWCNT, 0.1wt%GranularCNT, 0.5wt% SWCNT) Pin-on-disk Disk: Cr steel	Load:47.9N disk speed: 80rpm Ra=0.25 µm Lubricant: bovine albumin protein	1.12×10-6 mm3/Nm for UHMWPE 1.65×10-6 mm3/Nm for MWCNT 1.32×10-6 mm3/Nm for Granular CNT 1.46×10-6 mm3/Nm for SWCNT	Ploughing and scratching
Kanagaraj et al. (Kanagaraj et al., 2010)	UHMWPE(GUR1020)+ 0.2wt%CNT Ball-on-plate reciprocating sliding test Ball: alumina	Load: 12 N Sliding distance: 43.2-230.4m Stroke length: 4 mm	Reduction in wear volume in the range of 28-35% have seen for all sliding distances	Abrasion
Zoo et al. (Zoo et al., 2004)	UHMWPE+ 0.1-0.5wt%CNT Ball-on-disk Wear Tester Ball: Silicon Nitride	Load: 5 N Sliding speed: 0.3 m/sec	Wear loss is reduced in the range of 0.35-0.05mg on addition of CNT (0.1-0.5wt %)	Abrasion
S. Yousef et al. (Yousef et al., 2017)	UHMWPE (U) + 0.2wt% Paraffin oil (P) + 0.5-2wt%Carbon nano filler (C) Sample Code: UPC1/BM Pin-on-disk Pin: Ruby corundum	Load: 30 N Speed:60rpm Lubricant medium: air, artificial and natural	The specific wear found to be reduced by 42-86% for different lubricant medium ((in air, artificial and natural lubricant, respectively)	Abrasion
R. Manoj Kumar et al. (Kumar et al., 2019)	UHMWPE+ 0.1 wt% CNT Ball on disc Ball: Steel	Load: 5 N Sliding speed: 0.06 m/s Sliding Distance: 460 m Dry sliding	Chitosan and drug-loaded (UHMWPE/CNT and UHMWPE/CNT after drug release have shown 20% and 26% improvement in wear rate as compared to PE	Abrasion and Adhesion
LIU Jin-long [74]	HMWPE+bovine bone hydroxyapatite (BHA 20%) Ball-on-disc wear test	Load: 3.9 N Sliding speed: 0.21 m/s Testing time: 120 min	Reduction of 40% in the wear rate obtained for the UHMWPE/20% BHA composite	Ploughing Fatigue fracture

	Ball: Si3N4 ceramic ball Ball Dia: 4mm	Ra: 0.2μm		
Qingliang Wang [75]	UHMWPE/30%BHA (wt%) composite Ball-in socket hip Simulator Femoral head: CoCrMo alloy (Cr: 27.5%, Mo: 5.5%, Ni: 1.0%, Mn: 1.0%, Fe: 1.0%, C: 0.35%, Co: Bal)	Load: 1.15Kn Frequency: 1Hz Ra: 0.02μm	UHMWPE/30%BHA (wt%) composite obtains the wear rate is only about 46% of the wear rate of pure UHMWPE acetabular cup	Adhesive, Ploughing and Fatigue
Lei Xiong [79]	UHMWPE/nano-HAP composites Reciprocating tribometer Ball: CrCo Ball Dia: 9mm	Sliding speed: 50mm/s Stroke length: 25mm Frequency: 1Hz Contact stress: 3.54MPa Ra: 0.4-0.5μm	Wear rate is found approximately in range of (3.5-0.8)×10-6 mm3/Nm as GO content increase from (0-7wt%)	Abrasion
Alime Çolak [90]	RGO and UHMWPE Ball-on-disc wear test Ball: Al2O3 Ball Dia: 10mm	Load: 5N Sliding rate: 1.7cms-1 Testing time: 45min	Wear rate × 10-4 (mm3/Nm): UHMWPE- 5.62 UHMWPE/0.7RGO-5.24 UHMWPE/-RGO 5.45	Fatigue and Adhesive
J.A. Puértolas [89]	DLCH and UHMWPE Ball-on-disk wear test Ball: Alumina Ball Dia: 6mm	Load: 5.23N Sliding speed: 0.05m/s Ra: 0.05μm Temperature: 37°C	Wear rate -(2.4-3.0)×10-6 mm3/Nm Improve tribological properties have been obtained under bovine serum lubrication at a body temperature	Abrasive
M.J. Martíne Morlans [87]	GNP/UHMWPE-based composite. Ball-on-disk wear test Ball: Alumina Ball Dia: 6mm	Load: 5N Circular diameter of track: 4mm Contact pressure: 37MPa. Ra: 0.050μm Temperature: 37°C Sliding speed: 0.05m/s Sliding distance: 4320m	wear rate is found to be lowest at 0.5 wt% GNP, with a reduction of 20 and 15% for ball milling and blade mixing, respectively,	Abrasive and Adhesive
Zhixin Tai [85]	GO/UHMWPE composite.	Load: 5N	Wear rate is found approximately in	Abrasive and Fatigue

	GO (0-1 wt%) Ball-on-disc tribometer Ball: Zirconia Ball Dia: 4mm	Sliding speed: 9 cm/s Ra: 0.03µm Room Temperature	range of (1.8-1.2)×10-5 mm3/Nm as GO content increase from (0-3wt%)	

6.3 Effect of Hydroxyapatite-UHMWPE Composites on Biocompatibility and Wear Performance

Hydroxyapatite exhibits good biocompatibility while interacting with different human tissues, making it an interesting material to be used in orthopaedics (Roman-Lopez, Correcher, Garcia-Guinea, Rivera, & Lozano, 2014). The various composites of HA based composites have been studied in recent years in view of improved wear, mechanical and biological properties. The UHMWPE, filled with bovine HA, had been studied by Liu et al. (J.-L. Liu et al., 2008), and a wear test was performed on Universal Tribometer to evaluate the tribological performance against Si3N4 ceramic ball in the presence of human plasma lubrication (J.-L. Liu et al., 2008). They found a reduction in wear when the HA was added up to 30%, and the wear started to increase as soon as the HA concentration exceeded 30%. However, this increase in wear was observed to be less than that of pure UHMWPE. The addition of BHA in the UHMWPE matrix increased the modulus of elasticity and hardness of the composite simultaneously. The increase in modulus of elasticity lowered the adhesive forces, and the increase in hardness led to a decrease in ploughing forces. The summation of both forces lowered COF and wear rate in the BHA-UHMWPE composite. Wang et al. (Q. Wang, Liu, & Ge, 2009) also shown similar kind of findings. In addition they performed an experiment on the hip simulator in the presence of bovine serum and observed that the addition of HA (up to 30%) reduces the wear rate by 54% as compared to the wear rate of pure polymer and also found that an increase in bovine HA concentration from 30% to 40% reduced wear rate by 3% only (Q. Wang et al., 2009). In case of HA/UHMWPE composites the fatigue and abrasive wear mechanism were prominent to generate the wear particulates. The addition of HA reduces the sizes of worn-out particulates, and the percentage of particles greater than 10µm increases with bovine HA concentration. The particulates larger than 10µm reduce the tendency of aseptic loosening of joint prosthesis. Jiang et al. (Jiang, Jia, Wooley, & Yang, 2013) and Green et al. (Green, Fisher, Matthews, Stone, & Ingham, 2000) reported that particulates smaller than 10µm may activate macrophages and fibroblast to induce osteolysis, inflammatory response and aseptic loosening of joint prosthesis (Goodman et al., 2003; Green et al., 2000; Jiang et al., 2013; Q. Wang et al., 2009). Macuvele et al. (Macuvele et al., 2019) obtained UHMWPE/HA, and organophilic bentonite (UHMWPE/HA/BO) composites through planetary ball milling and compression molding. The addition of HA and BO reduced the coefficient of friction, and UHMWPE/HA/10%BO possesed a statistically lower coefficient of friction as compared to pure UHMWPE polymer, but they also observed that there is no statistical difference in coefficient of friction between UHMWPE/HA and UHMWPE/HA/10%BO. HA and UHMWPE did not exhibit any interaction between them. Macuvele et al. (Macuvele et al., 2019) suggested that the addition of BO changes the interaction between HA and UHMWPE through intercalation and exfoliation, reducing the friction coefficient. Schwartz et al. (Schwartz et al., 2007) and Xiong et al. (Xiong, Xiong, Yang, & Jin, 2011) also suggested that HA acts like a rigid point against the metallic counter surface in order to reduce the normal load and shear stress of the polymer and hence result in reduced wear rate (Macuvele et al., 2019; Schwartz et al., 2007; Xiong et al., 2011). Due to the formation of a thin transfer layer on the counter surface, which serves as an efficient barrier to prevent large-scale fragmentation of the polymer matrix, the wear rate of polymeric composites reinforced with BO is likely reduced (Mohan & Kanny, 2017). A detailed comparison of wear rate between HA-UHMWPE and pure UHMWPE has been presented in Figure 8 (a).

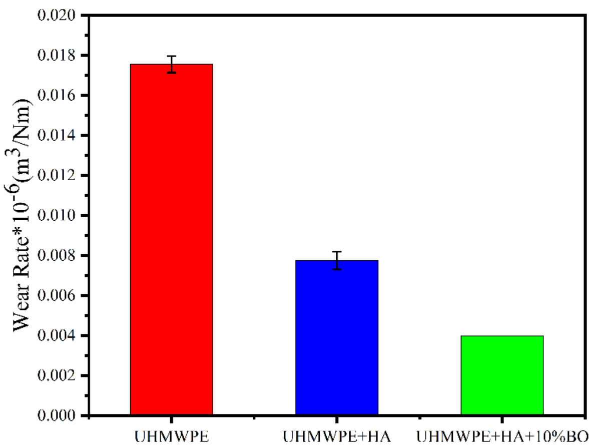
The HA-UHMWPE composites may improve the tribological performance of joint replacement implants without hampering the mechanical characteristics of the joint replacement implants. The synthesis of these composites is complex due to the high viscosity of UHMWPE bulk. The researchers may optimize the synthesis of particular composites to achieve the homogeneous distribution of these HA-UHMWPE composites

6.4 Effect of Graphene-Oxide-UHMWPE Composites on Wear Performance of Joint Implants

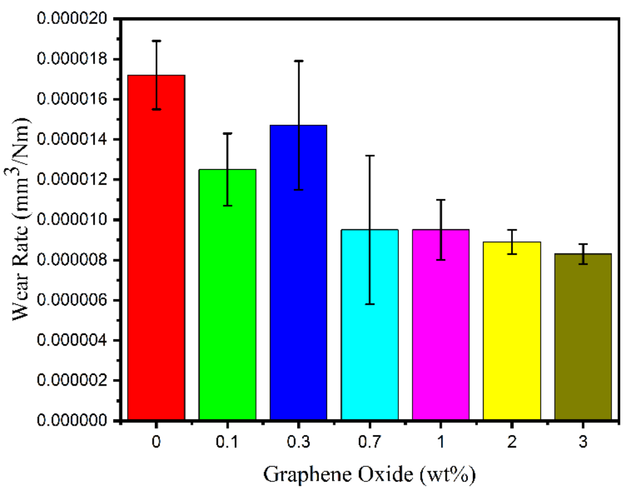
A surface oxygen functional group found on graphene oxide (GO) facilitates its dispersion in the selected matrix (Marques, Gonçalves, Singh, & Grácio, 2012; S Suñer & Emami, 2014). Chen et al. (Chen et al., 2012) used ultrasonicated dispersion method for preparing GO/UHMWPE composites and this composite shows relatively low wear and friction coefficient as compared to pure UHMWPE (Chen et al., 2012). Suñer and Emami (S Suñer & Emami, 2014) prepared GO/UHMWPE composite by means of ball milling and blending method, and thermometric analysis shown that the addition of GO in UHMWPE leads enhance thermal stability of composites, and it has a direct relation with the wear of composite. One more possible advantage of adding graphene is that the layers of graphene induce high lubrication in the tribological application, as detected in tribological findings in the past (Ou et al., 2010). Tai et al. (Tai, Chen, An, Yan, & Xue, 2012) observed an increased coefficient of friction for all GO concentrations and also found a 50% reduction in wear rate of GO/UHMWPE composites at a concentration of 3wt% GO the then pure UHMWPE. Lahiri et al. (Lahiri et al., 2014) also reported a reduction in wear rate while adding graphene nanoplatelet (GNP) in UHMWPE. They studied the effect of different concentrations of GNP reinforcement in UHMWPE and found wear is reduced by 2.5 and 4.5 times at 1wt% GNP for 200 μN and 300 μN, respectively.

Martínez-Morlanes et al. (Martínez-Morlanes, Pascual, Guerin, & Puértolas, 2021) developed a GNP coating over UHMWPE substrate for 0.1 -5 wt% concentration of non-functionalized GNPs and ball or blade mixing methods were used. A commercially available ball-on-disk Tribotester and deionized water were used to access wear resistance and coefficient of friction according to ASTM G99-17. They concluded that wear rate is affected by GNP content and wear rate was minimized at 0.5wt% of GNP concentration by 20% and 15% for ball and blade mixing methods respectively. The wear rates of Polyethylene against Al2O3 counterpart were found 20×10-7, which showed its consistency with previous studies (Haddadi, Saadatabadi, Kheradmand, Amini, & Ramezanzadeh, 2019; Puértolas et al., 2010). A wear track analysis showed that at low and high GNP content, different mechanisms were involved, similar to what was previously observed for RGO/UHMWPE composites (Çolak, Göktaş, & Mindivan, 2020; Martínez-Morlanes et al., 2021). The authors also observed grooves oriented parallel to the sliding direction on polyethylene surfaces, and abrasive, adhesive, and fatigue wear mechanisms were responsible for wear loss in all GNP concentrations. A detailed comparison of wear rate between GO-UHMWPE and pure UHMWPE has been presented in Figure 8 (b).

These findings suggest that graphene-based composites have shown elevated wear resistance compared to pure UHMWPE. These composites may be promising materials for joint replacement applications when they are induced to crosslinking or gamma irradiation or supplemented with vitamin E and articulate against textured counterface.



(a)



(b)

Figure 8: Schematic diagram showing wear rate of UHMWPE composites reinforced with: (a) HA (Macuvele et al., 2019), (b) Graphene Oxide (Tai et al., 2012).

A detailed comparison of reduction in wear rate for various composites has been summarized in Table. 2.

Table 2: Effect of various reinforcing materials on wear performance of UHMWPE (Baena, Wu, & Peng, 2015; Q. Wang et al., 2009).

Composite	Reduction in wear rate
CF/UHMWPE	56-58%
CNT/UHMWPE	26-86%
Graphene/UHMWPE	2.5-4.5 times
HA/UHMWPE	54-57%

6.5 Effect of Lubricants on Tribological Properties of UHMWPE Inserts

The type of lubricant and its protein concentration used in wear testing of joint replacement implants is a matter of debate among researchers all over the globe. The scientific community explored numerous possible lubricants such as distilled water, bovine serum, or synthetic oil and their compositions to gain the same wear behavior as it exists clinically (Affatato, Spinelli, Zavalloni, Mazzega-Fabbro, & Viceconti, 2008; Brown & Clarke, 2006).

The primary shortcoming of these lubricants is their protein precipitation which obscures the actual wear in polymer insert. The protein precipitation is commonly known as denaturation and Wang et al. (A. Wang, Essner, & Schmidig, 2004) suggested that this denaturation of lubricant may provide un-physiological protection against wear as it will behave like a solid lubricant. It is also evident from the literature that optimum protein concentration in lubricants is also a matter of controversy. In a natural synovial joint, 20-30 mg/ml protein concentration exists (Brown & Clarke, 2006; Saikko, 2003), therefore many researchers focussed their study on this concentration range, but it did not effectively provide boundary lubrication and even promotes wear of UHMWPE insert (Good et al., 2000; A. Wang, Schmidig, Essner, & Serekian, 2000).

Bovine serum (BS) is used as a lubricant in in-vitro studies carried out in joint simulators, producing the same wear similar to clinical wear. In spite of this, BS is not considered a standard lubricant because it tends to get contaminated, and its viscosity is also lower compared to the synovial fluid in natural joints (Bell et al., 2000; Yao, Laurent, Gilbertson, Jacobs, & Crowninshield, 2001). BS shows dual wear response to metal and UHMWPE counterpart. First, it shows increased wear on increasing protein concentration, after that gradually decreases wear on further addition of protein concentration. This happens due to BS denaturation i.e., protein precipitation, as it may act like a solid lubricant and shows reduced wear after denaturation (Harsha & Joyce, 2011; Maskiewicz, Williams, Prates, Bowsher, & Clarke, 2010; Saikko, 2003, 2005).

The lubricants based on Alpha Calf Serum (ACS) have shown their superiority against heat-induced protein precipitation (Saikko et al., 2021). Saikko et al. (Saikko et al., 2021) investigated the effect of protein type, and its temperature on the wear and friction of Vitamin-E highly crosslinked UHMWPE against CoCr. They performed a cold wear test to minimize the protein denaturation and bacterial growth. The serum lubricant was kept at 4°C in the refrigerator, and tests were carried out for the 4-37°C range of temperatures. The lowest wear rate was observed at refrigeration temperature and maximum at body temperature as the protein denaturation appears to be maximum at this temperature. The mean wear factor in ACS was reduced by two times as the temperature increases from 4°C -37°C. Only a five-degree drop in temperature, from 20°C to 15°C, caused the mean wear factor to rise by a factor of two. The mean k increased threefold when the temperature was lowered from 20 to 4°C as shown in Figure 9. DesJardins et al. (DesJardins et al., 2006) investigated the effect of bovine calf serum (50%) supplemented (1.5g/l) on the wear rate of UHMWPE. They found that the lubricant viscosity containing bovine calf serum and hyaluronic acid is similar to the fluid obtained from TKA joint fluid viscosity. Wear testing performed with Hyaluronic acid based bovine serum lubricants showed a similar wear pattern invivo.

The lubricant protein concentration and operating temperature are still a matter of debate among the researchers. These findings suggest that cold wear testing would be preferred in order to avoid microbial growth and protein denaturation, as these phenomena are dominant at elevated temperatures. The protein concentration within the lubricant could be optimized in order to see the realistic wear pattern as it can be seen in retrieved implants. Hyaluronic acid also plays a crucial role in maintaining lubricant viscosity at higher shear rates. Hyaluronic acid may be added to the bovine serum in order to get a lubricant that has similar rheological characteristics as joint replacement fluid while performing the wear experiments for joint implants.

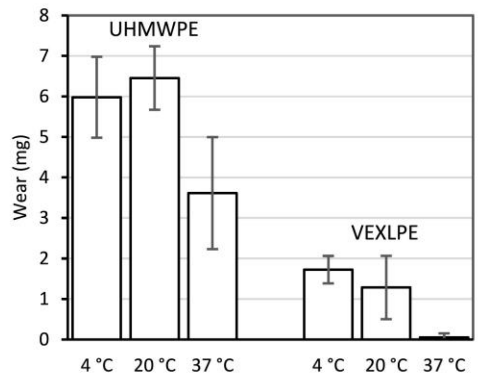


Figure 9: Variation of wear rate with Temperature in diluted alpha calf serum (Saikko et al., 2022).

6.6 Effect of Surface Texture Modulation on Tribological Properties Of UHMWPE

Smooth counterface of metallic component in arthroplasties applications is always desirable to reduce the wear debris volume and it also change wear mechanism from abrasive to adhesive mode. The volume and morphology of wear particulates can be controlled by well-argued surface contour of metallic part. Nakanishi et al (Nakanishi et al., 2018) studied effects of surface profile of Co-28Cr-6Mo alloy on the wear of UHMWPE using Pin-on-Disk tribometer under fetal calf serum lubrication. The surface of Co-28Cr-6Mo alloy disk was designed in a way so that it controls not only volume of but also morphology of wear particulates. The surface roughness of Co-Cr-Mo alloy recorded in order of millimeter to nanometer as well as surface is curved with concave and convex parts. The surface was processed with micro slurry jet erosion technique. As a result of a waviness curve within a millimetre scale that has convex and concave parts, the parts of the Co-Cr-Mo alloy and the UHMWPE in direct contact will be semi-dry, resulting in the transfer of the polyethylene film onto the alloy, resulting in an increase in size of polyethylene debris. They used three different surfaces having different value of surface roughness ranging from 0.001µm-0.012µm. The specific wear rate of polyethylene for surface 2 (Ra=0.002 µm, depth=0.270, pitch=1mm) is lower than that for surface 1 (Ra=0.005 µm, depth=0.809, pitch=1mm) and surface 3 (Ra=0.001 µm, depth=0.349, pitch=3mm) and the graphical representation is shown in Figure 10. Furthermore, a given number of cycles resulted in a reduction of around 25% of the specific wear rate for textured surfaces 1 (Ra=0.005 µm, depth=0.809, pitch=1mm) and 70% for surfaces 2 (Ra=0.002 µm, depth=0.270, pitch=1mm) respectively, when compared to untextured surfaces (Ra = 0.12m Ra, depth=0) and can be seen in Figure 10. Texture on the disc surface boost hydrodynamic pressure by promoting film formation and also serves as lubrication reservoirs. The hydrodynamic action pressurises the joint fluid while simultaneously increasing the space between the alloys and the UHMWPE bearings, reducing wear and friction on the UHMWPE bearing surface. For surface 1, the distance between the convex and concave parts is greater than in surface 2, resulting in an abrasive wear mechanism.

Langhorn et al. (Langhorn, Borjali, Hippensteel, Nelson, & Raeymaekers, 2018) worked on micro-texturing effect of Co-Cr-Mo on wear rate of HXPE pin. The multidirectional shear with bovine serum lubrication constituting 64.8mg/ml protein concentration, and Paul loading were applied to assess wear performance of HXPE contacting with micro-textured Co-Cr-Mo surface. They reported that the wear rate was reduced by 50% for micro-textured surfaces as compared to non-textured surface. However, the microtextured surface had shown slight increase in surface roughness after wear test, indicating reduced wear due to lubrication film formation. Borjali et al. (Borjali, Langhorn, Monson, & Raeymaekers, 2017) also worked on surface texture modification in view of observing reduced wear of polymer insert in joint prosthesis. They proposed a direct correlation between polyethylene wear rate and surface texture due to formation lubricating film as increase in film thickness leads to decrease in contact area and hence reduced friction and wear are observed (Borjali et al., 2017; Chyr et al., 2014; Qiu, Chyr, Sanders, & Raeymaekers, 2014; Qiu, Minson, & Raeymaekers, 2013).

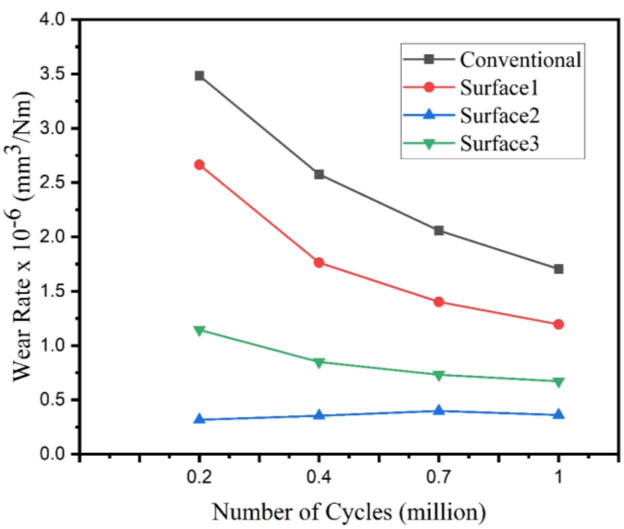


Figure 10: Specific wear rate of the as-pinned specimens with ultra-high molecular weight (Nakanishi et al., 2018).

Typically, the tribological performance of artificial joints would improve with the decrease of surface roughness. However, there may be a critical value of surface roughness below which the friction coefficient would step up again. Thus, finding the critical points for different material combinations should be the focus of interest. Another approach is to use texture technology to improve the tribological performance of artificial joints. The three functions provided by surface texture are trapping wear particles, reserving lubricant, and providing hydrodynamic pressure. However, there exist no systematic research on the shape, size and distribution of texture patterns till date.

7.0 MODELLING OF TRIBOLOGICAL PARAMETERS AFFECTING WEAR OF UHMWPE IN TOTAL JOINT REPLACEMENTS

Above literature reveals that wear of implants is quite a complex phenomenon therefore many modelling approaches have been taken up for the ease of tribological analysis of implants for eg. Experimental modelling, mathematical modelling, Machine learning based modelling etc. in order to evaluate tribological characteristics of joint replacement implants, Pin-On-Disk trials were carried out based on their operating parameters and environmental conditions. Though the in-vitro research is a critical strategy for assessing the wear performance of PE bearing materials and TKR geometry, these studies are expensive and time-consuming. Another modeling approach on which researchers have focussed is computation wear modeling. Literature reveals that there are many mathematical models based on either Archard's Law or modified Archard's Law. These wear models are primarily based on contact area, contact stresses, sliding distance, and wear factor (Abdelgaied, Fisher, & Jennings, 2018; Innocenti, Labey, Kamali, Pascale, & Pianigiani, 2014; Willing & Kim, 2009; Zhao, Sakoda, Sawyer, Banks, & Fregly, 2008). A new parameter, cross-shear ratio, was introduced to account the effect of multi-directional motion (T. Johnson, Laurent, Yao, & Gilbertson, 2001; A. Wang, 2001). However, the above cited models do not include the cross-shear ratio effect and hence do not show the effect of reported parameters on wear performance of joint implants. Most previously proposed cross-shear ratio models were time-independent, which implies that the molecular orientation of polyethylene lamella was fixed in a single direction with regard to time, which is not clinically correct for estimating the wear rate of polyethylene (O'Brien, Bohm, Petrak, Wyss, & Brandt, 2014). Machine learning is another major modelling technique that scientists, engineers, and researchers in the field of wear modeling are considering these days. In machine learning, algorithms and statistical models are developed that allow computer systems to learn from data without being explicitly programmed, improving their performance on a specific task (Mahesh, 2020). In other words, the goal of machine learning is for computers to acquire knowledge by learning and adapting to new experiences, allowing them to identify patterns, make predictions, and make decisions automatically. It is used in many different fields of sciences and engineering including image classification, natural language processing, healthcare diagnostics, mechanical and tribological characteristics prediction, prediction of hardness of cast iron, heart-rate estimation, fatigue detection associated with physical activities etc (Das et al., 2018; Fragassa, Babic, & Domingues dos Santos, 2020; Hooda, Joshi, & Shah, 2021; Vipin Kumar & Tewari, 2023)

7.1 Machine Learning Algorithms

Artificial Neural Network (ANN)

ANNs are computational models which always tries to mimic the structure and function of human brain. ANNs comprises of interconnected neurons arranged in layers. Neurons receive input, perform mathematical operations, and pass the result to the next layer to process the information. ANNs learn from experience i.e. training data and try to establish a relationship between input and output. Based on that relationship, ANN predicts output for an unknown input dataset.

The neurons in each successive layer of the ANN acquire their input from all the neurons in the preceding layer as follows (Jaf et al., 2024) :

$$\theta = \sum_{i}^{n} w_i x_i + b \tag{1}$$

Where, *w* and *x* are weight associated with the input variable and input variable respectively.
Artificial Neural Networks (ANNs) are well-known for their capacity to manage complicated non-linear interactions, which makes them ideal for big-data applications. While ANNs may be modified for small datasets, their prediction ability on such datasets is sometimes viewed as a drawback.

k-nearest neighbor (KNN)

KNN is a well-known ML model which has been extensively used in both classification and regression problems. Using KNN, new data points are predicted based on distance functions, and the predicted output is based on the closest data points (neighbors) in training dataset. The weights to the nearest neighbors are assigned in such a way that nearest datapoints have more contribution than distant datapoint in overall prediction of target variable. The mathematical expression for prediction of target variable is given as follows (Sun et al., 2022):

$$\hat{y} = \frac{1}{k} \sum_{i=1}^{k} y_i(X) \tag{2}$$

The number of nearest neighbors is the deciding factor in prediction for new datapoint. The poor generalization observed for new data points due to overfitting is often seen in case of small number of nearest neighbors and may fail to address sensitivity in case of very large numbers of nearest neighbors. Therefore, proper adjustment of the number of nearest neighbors is needed in order to get an optimum model for target prediction.

Random Forest (RF)

RF is basically an ensemble technique which combines the prediction of multiple decision trees in order to get the prediction for new datapoint. RF regression algorithms are based on row sampling and column sampling, meaning they always use subsets of a dataset for each decision tree. This way, RF regression model builds a series of decision trees and then averages the predictions from each decision tree to predict UHMWPE specific wear rate.
A measure of feature importance is also provided by RF Regression, which can help determine which features are most likely to predict target variable. The mathematical of prediction through RF model is given as follows (Rodriguez-Galiano, Sanchez-Castillo, Chica-Olmo, & Chica-Rivas, 2015):

$$\bar{y} = \frac{1}{n} \sum_{i=1}^{n} y\left(x, \theta_i\right) \tag{3}$$

Because each Random Forest decision tree is trained on a portion of the data, it is resistant to noise and outliers. But this may also result in overfitting, and this overfitting can be avoided by adjusting the Random Forest's hyperparameters including the number of trees in the forest and the maximum depth of each tree.

Support Vector Machines (SVM)

The SVM approach is often used in classification, but it also works for regression problem. SVR aims to fit a regression line that best predicts continuous target variable values for given input feature. The data in hyperplanes is arranged through various types of kernel functions including linear, polynomial, radial basis and sigmoid kernel functions. The SVM technique predicts a given wear rate while minimizing the regression coefficient, which reduces mean squared error. SVM approach well suited for small dataset with large number of input features. The mathematical expression of objective function and constraints are given as follows (Koya, Aneja, Gupta, & Valeo, 2022):

$$\min \frac{\beta^2}{2} + C\sum_{i=0}^{n} \varepsilon \quad (4)$$

$$y_i - b_0 x_i \leq \varepsilon + \delta \quad (5)$$

ERMİŞ and Hüseyin (ERMİŞ & Hüseyin) used a stainless steel disk, which is sliding against UHMWPE polymer, to run the POD trials under different loading and sliding speed conditions ranging between 38-150 N and 0.4-1.5 m/s, respectively. They have further investigated the applicability of Artificial Neural Networks (ANN) in the prediction of coefficient of friction and wear rate for various sliding conditions and found ANN modeling has good agreement with the respective experimental values with 0.004% and 1.0 relative error, coefficient of determination respectively.

Adss et al. (Adss, Mahmoud, Zakaria, & Khalifa) developed a Neural Network (NN) model, trained with an experimental Pin-on-Ring based dataset, and the effect of load, sliding speed and lubricant type on wear rate is predicted using the developed NN model. They have also suggested that NN model predictions have good agreement with their experimental values.

Kumar et al. (Vipin Kumar & Tewari, 2023) developed an ANN model based on non-dimensional contact stress, cross-shear ratio and stroke length to predict the wear rate in UHMWPE sample for total knee replacement implants. The illustration ANN structure has been shown in Figure 11. They achieved an accuracy of 99% while training and testing the ANN model with a dataset that has 50×10^3 instances.

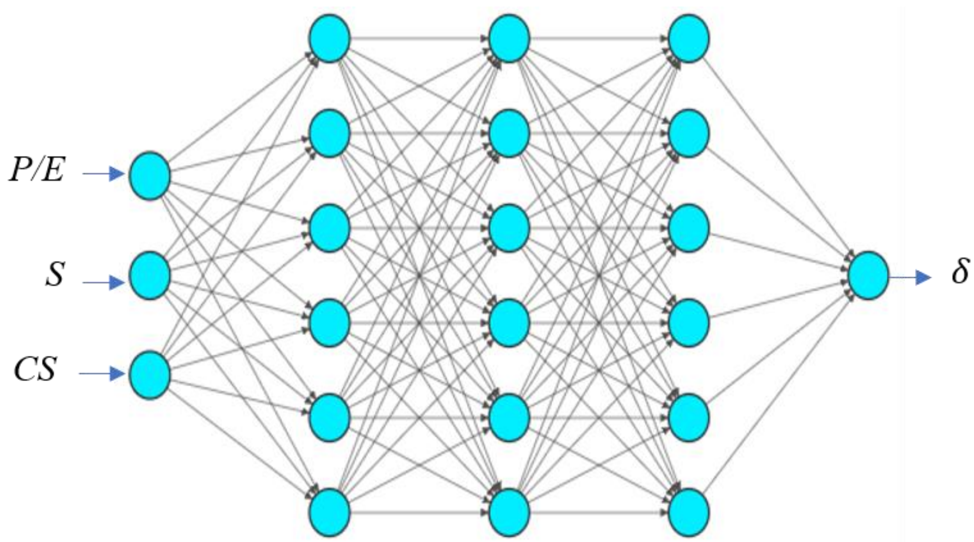


Figure 11: Multilayer ANN model (Vipin Kumar & Tewari, 2023).

Kumar et al. (Kumara, Tewaria, Pandeya, & Rawata, 2023) also developed ML models to predict linear wear depth in TKR by taking non-dimension contact stress, stroke length and cross-shear ratio as an input variable. They successfully predicted linear wear depth with an accuracy of 99% with RF models.

Borjali et al. (Borjali et al., 2019) incorporated ML based models to predict the wear rate of UHMWPE insert for hip replacement implants. They aggregated the data from the previous research, and the same data is used for the training and testing of ML based models. It has also been observed that ML based models have great potential to predict the wear rate for new Pin-on-Disk experiments with process attributes that lie in the range of the dataset used for training the model. Authors also found that a instance-based KNN model is the best model as compared to other machine learning methods with R2, MAE, and RSME values equal to 0.91, 1.38 and 2.37 respectively. They also reported that the contact area is the most significant parameter followed by radiation dose, normal load, disk surface roughness, wear path aspect ratio, test duration, and sliding distance per cycle respectively.

Mohammed et al. (Mohammed, Mohammed, & Mohammed, 2023) predicted the tribological characteristics such as coefficient of friction (COF) and specific wear rate (SWR) of UHMWPE reinforced with silicon carbide (SiC) using five different machine learning algorithms named Random forest (RF), decision tree (DT), k-nearest neighbor (KNN), support vector machines (SVM), and ANN. The concentration of SiC, holding time, and pressure applied are input parameters, and COF and SWR are taken as target features. Out of these five ML algorithms, the SVM model predicted COF and SWR with 99.99% and 99.98%, respectively.

Further, Vinoth et al. (Vinoth et al., 2021) designed a UHMWPE hybrid composite for acetabular cups used in hip replacement implants using machine learning approaches. ANN model has been developed with MWCNT, graphene, and CF as input features and taking mechanical and wear properties as target features. Further genetic algorithm-based optimization has been performed in order to make a composite with enhanced properties. The specific wear rate has been predicted using the ANN model with an R2 value of 0.8029.

Similalry, Kurt and Oduncuoglu (Kurt & Oduncuoglu, 2015) have studied the effect of various input features, viz. weight percentages of reinforcements sliding speed, type, and applied load over the volume loss of UHMWPE using feed forward back propagation neural network. They have successfully predicted the volume loss of UHMWPE-based composites with R2 0.80 and 4.1% mean absolute error.

Deshpande et al. (Deshpande et al., 2024) employed the ML algorithms in the classification of progressive wear in UHMWPE under pin-on-disk test conditions. They applied manual feature extraction and convolutional neural network (CNN) and reported superior classification performance of CNN within the range of 94-96%.

Haribabu et. al. (Haribabu & Basu, 2024) used ML models in prediction of biomechanical response of the acetabulum of hip implant. They computed biomechanical response of different acetabular liner including HA-AL_2O_{3}- HDPE, highly crosslinked UHMWPE and ZTA and reported that Random Forest model shown superior prediction capability with 0.97-0.99 R^2 value.

The above literature suggests that ML modeling could be another alternative to costly and time-consuming wear experimentation. ML modelling has shown its potential while predicting the tribological characteristics of UHMWPE and its composites based on its operating parameters, which is not possible with traditional tribological experiments. Most of these studies have taken a small dataset to train and test the ML algorithms, which hampers the accuracy of ML models. The performance of ML models can be improved if trained with a larger dataset. These studies are based on only a few parameters on which wear rate or COF is dependent. Therefore, in the future, researchers may incorporate more parameters such as lubrication protein concentrations, cross-shear ratio, operating temperature etc. to establish a better model using Machine learning

CONCLUSIONS

The current review focuses on the effect of different reinforcing materials viz. CF, CNT, HA, and graphene in bulk UHMWPE, on wear and coefficient of friction in total joint arthroplasties. Also, the effect of lubrication protein concentration, lubrication biochemistry, and application of machine learning algorithms in wear predictions of total joint replacement prosthesis have been reviewed. The summary and future scope of reviewed literature has been presented in points as given below.

a. The addition of CF, CNT, HA and graphene influences the wear performance to bearing surfaces in a positive manner. An increase in CNT concentration has shown reduced wear by 20%-80% compared to pure UHMWPE.
b. A reduction in wear resistance is observed with graphene as reinforcing material and the wear factor is observed to be decreased by fourfold as compared to pure UHMWPE. In order to fabricate effective CNT/UHMWPE and graphene /UHMWPE which have the capability to replace highly crosslinked polyethylene bearing surface, further tribological assessment is required. The tribological experiments should be performed under more realistic kinematics and kinetics which are encountered in daily activities.
c. The cytotoxicity is also a matter of concern in CNT/UHMWPE and graphene/UHMWPE composites before being applied in total joint replacements. The evaluation of biological characteristics and antimicrobial activity of wear debris, generated through these composites are also an important factor.
d. According to the literature survey, wear debris generated with these composites are the prime reason for bone osteolysis; therefore, their characterization is necessary as the

particulates of size 0.1-1μm are biologically active and causes osteolysis and implants loosening.

e. The surface roughness of hard metal surface also plays a crucial role in wear performance of joint prosthesis. It is evident from literature after reduction of surface roughness upto a certain level, wear rate of UHMWPE polymer starts increasing. Enough evidences are not available regarding critical value of surface roughness.
f. The trapping of wear debris in textured surfaces are also a serious Further, nowadays, Machine Learning is also an interesting area of research for various applications. Only a few works of literature are available in the tribological assessment of total joint replacement implants.
g. Machine learning operates from the dataset, including input and target attributes for eg. contact area, normal load, wear path shape, frequency, average disc surface roughness, lubricant temperature, wear path aspect ratio, sliding distance per cycle, lubricant protein concentration, test duration, and polyethylene radiation dose. There needs to be clarity on the importance of the parameter to predict the wear rate based on operating parameters.
h. According to literature survey, the prediction performance of ML models is totally depending upon the type of dataset and hyperparameter tuning. ANNs are suitable for large dataset. In KNN models, the selection of nearest neighbors is an important factor as it can be seen with very small number of nearest neighbors. In case RF models, overfitting can be avoided by tuning the number of trees and max_depth of each tree. On the other hand, the SVM is well suited for dataset having small number of datapoints and large number of input variable.
i. Therefore, more research is needed to evaluate correct wear behavior with high accuracy using Machine learning so that importance of Machine learning may be highlighted and developed for future researchers of the area.

REFERENCES

Abaricia, J. O., Shah, A. H., & Olivares-Navarrete, R. (2021). Substrate stiffness induces neutrophil extracellular trap (NET) formation through focal adhesion kinase activation. Biomaterials, 271, 120715.

Abdelgaied, A., Fisher, J., & Jennings, L. (2018). A comprehensive combined experimental and computational framework for pre-clinical wear simulation of total knee replacements. Journal of the mechanical behavior of biomedical materials, 78, 282-291.

Abu-Amer, Y., Darwech, I., & Clohisy, J. C. (2007). Aseptic loosening of total joint replacements: mechanisms underlying osteolysis and potential therapies. Arthritis research & therapy, 9(1), 1-7.

Adss, D., Mahmoud, T., Zakaria, H., & Khalifa, T. Prediction of the wear behavior of UHMWPE using artificial neural networks.

Affatato, S. (2012). Wear of orthopaedic implants and artificial joints: Elsevier.

Affatato, S., Bracco, P., Costa, L., Villa, T., Quaglini, V., & Toni, A. (2012). In vitro wear performance of standard, crosslinked, and vitamin-E-blended UHMWPE. Journal of Biomedical Materials Research Part A, 100(3), 554-560.

Affatato, S., Spinelli, M., Zavalloni, M., Mazzega-Fabbro, C., & Viceconti, M. (2008). Tribology and total hip joint replacement: current concepts in mechanical simulation. Medical engineering & physics, 30(10), 1305-1317.

Alhasan, H., Terkawi, M. A., Matsumae, G., Ebata, T., Tian, Y., Shimizu, T., . . . M Abd Elwakil, M. (2022). Inhibitory role of Annexin A1 in pathological bone resorption and therapeutic implications in periprosthetic osteolysis. Nature communications, 13(1), 1-13.

Ansari, F., Ries, M. D., & Pruitt, L. (2016). Effect of processing, sterilization and crosslinking on UHMWPE fatigue fracture and fatigue wear mechanisms in joint arthroplasty. Journal of the mechanical behavior of biomedical materials, 53, 329-340.

Baena, J. C., Wu, J., & Peng, Z. (2015). Wear performance of UHMWPE and reinforced UHMWPE composites in arthroplasty applications: a review. Lubricants, 3(2), 413-436.

Balagna, C., Spriano, S., & Faga, M. (2012). Characterization of Co–Cr–Mo alloys after a thermal treatment for high wear resistance. Materials Science and Engineering: C, 32(7), 1868-1877.

Bell, J., Besong, A., Tipper, J., Ingham, E., Wroblewski, B., Stone, M., & Fisher, J. (2000). Influence of gelatin and bovine serum lubricants on ultra-high molecular weight polyethylene wear debris generated in in vitro simulations. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 214(5), 513-518.

Borjali, A., Langhorn, J., Monson, K., & Raeymaekers, B. (2017). Using a patterned microtexture to reduce polyethylene wear in metal-on-polyethylene prosthetic bearing couples. Wear, 392, 77-83.

Borjali, A., Monson, K., & Raeymaekers, B. (2019). Predicting the polyethylene wear rate in pin-on-disc experiments in the context of prosthetic hip implants: Deriving a data-driven model using machine learning methods. Tribology International, 133, 101-110.

Bracco, P., & Oral, E. (2011). Vitamin E-stabilized UHMWPE for total joint implants: a review. Clinical Orthopaedics and Related Research®, 469(8), 2286-2293.

Brach del Prever, E. M., Bistolfi, A., Bracco, P., & Costa, L. (2009). UHMWPE for arthroplasty: past or future? Journal of Orthopaedics and Traumatology, 10(1), 1-8.

Brandt, J.-M., Charron, K., Zhao, L., MacDonald, S., & Medley, J. (2021). Lubricant biochemistry affects polyethylene wear in knee simulator testing. Biotribology, 27, 100185.

Brandt, J.-M., Charron, K., Zhao, L., MacDonald, S. J., & Medley, J. B. (2012). Calf serum constituent fractions influence polyethylene wear and microbial growth in knee simulator testing. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 226(6), 427-440.

Brandt, J. M., Brière, L., Marr, J., MacDonald, S., Bourne, R., & Medley, J. (2010). Biochemical comparisons of osteoarthritic human synovial fluid with calf sera used in knee simulator wear testing. Journal of Biomedical Materials Research Part A, 94(3), 961-971.

Brown, S. S., & Clarke, I. C. (2006). A review of lubrication conditions for wear simulation in artificial hip replacements. Tribology Transactions, 49(1), 72-78.

Buford, A., & Goswami, T. (2004). Review of wear mechanisms in hip implants: Paper I–General. Materials & Design, 25(5), 385-393.

Cao, S., Liu, H., Ge, S., & Wu, G. (2011). Mechanical and tribological behaviors of UHMWPE composites filled with basalt fibers. Journal of reinforced plastics and composites, 30(4), 347-355.

Chen, Y., Qi, Y., Tai, Z., Yan, X., Zhu, F., & Xue, Q. (2012). Preparation, mechanical properties and biocompatibility of graphene oxide/ultrahigh molecular weight polyethylene composites. European Polymer Journal, 48(6), 1026-1033.

Chukov, D., Stepashkin, A., Maksimkin, A., Tcherdyntsev, V., Kaloshkin, S., Kuskov, K., & Bugakov, V. (2015). Investigation of structure, mechanical and tribological properties of short carbon fiber reinforced UHMWPE-matrix composites. Composites Part B: Engineering, 76, 79-88.

Chyr, A., Qiu, M., Speltz, J. W., Jacobsen, R. L., Sanders, A. P., & Raeymaekers, B. (2014). A patterned microtexture to reduce friction and increase longevity of prosthetic hip joints. Wear, 315(1-2), 51-57.

Colaco, R., Gispert, M., Serro, A., & Saramago, B. (2007). An energy-based model for the wear of UHMWPE. Tribology Letters, 26(2), 119-124.

Çolak, A., Göktaş, M., & Mindivan, F. (2020). Effect of reduced graphene oxide amount on the tribological properties of UHMWPE biocomposites under water-lubricated conditions. SN Applied Sciences, 2(3), 1-7.

Couto, M., Vasconcelos, D. P., Sousa, D. M., Sousa, B., Conceição, F., Neto, E., . . . Alves, C. J. (2020). The mechanisms underlying the biological response to wear debris in periprosthetic inflammation. Frontiers in Materials, 7, 274.

Dangsheng, X. (2005). Friction and wear properties of UHMWPE composites reinforced with carbon fiber. Materials letters, 59(2-3), 175-179.

Das, A., Pradhapan, P., Groenendaal, W., Adiraju, P., Rajan, R. T., Catthoor, F., . . . Van Hoof, C. (2018). Unsupervised heart-rate estimation in wearables with liquid states and a probabilistic readout. Neural networks, 99, 134-147.

Datta, S., & Chattopadhyay, P. (2013). Soft computing techniques in advancement of structural metals. International Materials Reviews, 58(8), 475-504.

Deshpande, P., Wasmer, K., Imwinkelried, T., Heuberger, R., Dreyer, M., Weisse, B., . . . Pandiyan, V. (2024). Classification of Progressive Wear on a Multi-Directional Pin-on-Disc Tribometer Simulating Conditions in Human Joints-UHMWPE against CoCrMo Using Acoustic Emission and Machine Learning. Lubricants, 12(2), 47.

DesJardins, J., Aurora, A., Tanner, S., Pace, T., Acampora, K., & LaBerge, M. (2006). Increased total knee arthroplasty ultra-high molecular weight polyethylene wear using a clinically relevant hyaluronic acid simulator lubricant. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 220(5), 609-623.

ERMİŞ, K., & Hüseyin, Ü. Tribological Behavior of Ultra-High Molecular Weight Polyethylene Polymer with Artificial Neural Network Modeling. Kocaeli Journal of Science and Engineering, 4(2), 171-178.

Fabry, C., Zietz, C., Dammer, R., & Bader, R. (2015). 12 patterns of wear in total knee replacement. In The Unhappy Total Knee Replacement (pp. 135-145): Springer.

Fam, H., Kontopoulou, M., & Bryant, J. (2009). Effect of concentration and molecular weight on the rheology of hyaluronic acid/bovine calf serum solutions. Biorheology, 46(1), 31-43.

Fang, J., Dong, L., Dong, W., Chiang, S. W., Makimattila, S., Du, H., . . . Kang, F. (2015). Freeze-drying method prepared UHMWPE/CNT s composites with optimized micromorphologies and improved tribological performance. Journal of Applied Polymer Science, 132(18).

Fragassa, C., Babic, M., & Domingues dos Santos, E. (2020). Machine learning approaches to predict the hardness of cast iron. Tribology in Industry, 42(1), 1-9.

Fu, J., Doshi, B. N., Oral, E., & Muratoglu, O. K. (2013). High temperature melted, radiation cross-linked, vitamin E stabilized oxidation resistant UHMWPE with low wear and high impact strength. Polymer, 54(1), 199-209.

Gallo, J., Vaculova, J., Goodman, S. B., Konttinen, Y. T., & Thyssen, J. P. (2014). Contributions of human tissue analysis to understanding the mechanisms of loosening and osteolysis in total hip replacement. Acta biomaterialia, 10(6), 2354-2366.

Good, V. D., Clarke, I. C., Gustafson, G. A., Downs, B., Anissian, L., & Sorensen, K. (2000). Wear of ultra-high molecular weight polyethylene and polytetrafluoroethylene in a hip simulator: a dose-response study of protein concentration. Acta Orthopaedica Scandinavica, 71(4), 365-369.

Goodman, S. B., Song, Y., Yoo, J. Y., Fox, N., Trindade, M. C., Kajiyama, G., . . . Smith, R. L. (2003). Local infusion of FGF-2 enhances bone ingrowth in rabbit chambers in the presence of polyethylene particles. Journal of Biomedical Materials Research Part A: An Official Journal of The Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials, 65(4), 454-461.

Green, T. R., Fisher, J., Matthews, J. B., Stone, M. H., & Ingham, E. (2000). Effect of size and dose on bone resorption activity of macrophages by in vitro clinically relevant ultra high molecular weight polyethylene particles. Journal of Biomedical Materials Research: An Official Journal of The Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials, 53(5), 490-497.

Grobbelaar, C., Du Plessis, T., & Marais, F. (1978). The radiation improvement of polyethylene prostheses. A preliminary study. The Journal of Bone & Joint Surgery British Volume, 60(3), 370-374.

Guedes, R. M., Kanagaraj, S., Sreekanth, P., Oliveira, M., & Fonseca, M. (2015). Ultra high molecular weight polyethylene and its reinforcement with carbon nanotubes in medical devices. Polyethylene-Based Blends, Composites and Nanocomposities, 201.

Haddadi, S. A., Saadatabadi, A. R., Kheradmand, A., Amini, M., & Ramezanzadeh, M. (2019). SiO2-covered graphene oxide nanohybrids for in situ preparation of UHMWPE/GO (SiO2) nanocomposites with superior mechanical and tribological properties. Journal of Applied Polymer Science, 136(31), 47796.

Haribabu, G. N., & Basu, B. (2024). Implementing Machine Learning approaches for accelerated prediction of biomechanical response in acetabulum of a hip joint. Journal of the mechanical behavior of biomedical materials, 106495.

Harsha, A., & Joyce, T. (2011). Challenges associated with using bovine serum in wear testing orthopaedic biopolymers. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 225(10), 948-958.

Hasan, M. S., Kordijazi, A., Rohatgi, P. K., & Nosonovsky, M. (2021). Triboinformatic modeling of dry friction and wear of aluminum base alloys using machine learning algorithms. Tribology International, 161, 107065.

Hasan, M. S., Kordijazi, A., Rohatgi, P. K., & Nosonovsky, M. (2022a). Application of Triboinformatics Approach in Tribological Studies of Aluminum Alloys and Aluminum-Graphite Metal Matrix Composites. In Metal-Matrix Composites (pp. 41-51): Springer.

Hasan, M. S., Kordijazi, A., Rohatgi, P. K., & Nosonovsky, M. (2022b). Machine learning models of the transition from solid to liquid lubricated friction and wear in aluminum-graphite composites. Tribology International, 165, 107326.
Hasan, M. S., Kordijazi, A., Rohatgi, P. K., & Nosonovsky, M. (2022c). Triboinformatics Approach for friction and wear prediction of al-graphite composites using machine learning methods. Journal of Tribology, 144(1).
Hasan, M. S., & Nosonovsky, M. (2021). Topological data analysis for friction modeling. EPL (Europhysics Letters), 135(5), 56001.
Hirakawa, K., Jacobs, J. J., Urban, R., & Saito, T. (2004). Mechanisms of failure of total hip replacements: lessons learned from retrieval studies. Clinical Orthopaedics and Related Research (1976-2007), 420, 10-17.
Hodges, N. A., Sussman, E. M., & Stegemann, J. P. (2021). Aseptic and septic prosthetic joint loosening: Impact of biomaterial wear on immune cell function, inflammation, and infection. Biomaterials, 278, 121127.
Hooda, R., Joshi, V., & Shah, M. (2021). A comprehensive review of approaches to detect fatigue using machine learning techniques. Chronic Diseases and Translational Medicine.
Huber, N., & Tsakmakis, C. (2001). A neural network tool for identifying the material parameters of a finite deformation viscoplasticity model with static recovery. Computer Methods in Applied Mechanics and Engineering, 191(3-5), 353-384.
Ingham, E., & Fisher, J. (2005). The role of macrophages in osteolysis of total joint replacement. Biomaterials, 26(11), 1271-1286.
Innocenti, B., Labey, L., Kamali, A., Pascale, W., & Pianigiani, S. (2014). Development and validation of a wear model to predict polyethylene wear in a total knee arthroplasty: a finite element analysis. Lubricants, 2(4), 193-205.
Jaf, D. K. I., Abdalla, A., Mohammed, A. S., Abdulrahman, P. I., Kurda, R., & Mohammed, A. A. (2024). Hybrid nonlinear regression model versus MARS, MEP, and ANN to evaluate the effect of the size and content of waste tire rubber on the compressive strength of concrete. Heliyon.
Jiang, Y., Jia, T., Wooley, P. H., & Yang, S.-Y. (2013). Current research in the pathogenesis of aseptic implant loosening associated with particulate wear debris. Acta Orthop Belg, 79(1), 1-9.
Johnson, B. B., Santare, M. H., Novotny, J. E., & Advani, S. G. (2009). Wear behavior of carbon nanotube/high density polyethylene composites. Mechanics of Materials, 41(10), 1108-1115.
Johnson, T., Laurent, M., Yao, J., & Gilbertson, L. (2001). The effect of displacement control input parameters on tibiofemoral prosthetic knee wear. Wear, 250(1-12), 222-226.
Kaddick, C., & Wimmer, M. (2001). Hip simulator wear testing according to the newly introduced standard ISO 14242. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 215(5), 429-442.
Kanagaraj, S., Mathew, M., Fonseca, A., Oliveira, M., Simoes, J., & Rocha, L. (2010). Tribological characterisation of carbon nanotubes/ultrahigh molecular weight polyethylene composites: the effect of sliding distance. International Journal of Surface Science and Engineering, 4(4-6), 305-321.

Kilgour, A., & Elfick, A. (2009). Influence of crosslinked polyethylene structure on wear of joint replacements. Tribology International, 42(11-12), 1582-1594.
Koerten, H., Onderwater, J., Koerten, E., Bernoski, F., & Nelissen, R. (2001). Observations at the articular surface of hip prostheses: an analytical electron microscopy study on wear and

corrosion. Journal of Biomedical Materials Research: An Official Journal of The Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials, 54(4), 591-596.

Koya, B. P., Aneja, S., Gupta, R., & Valeo, C. (2022). Comparative analysis of different machine learning algorithms to predict mechanical properties of concrete. Mechanics of Advanced Materials and Structures, 29(25), 4032-4043.

Kremers, H. M., Larson, D. R., Crowson, C. S., Kremers, W. K., Washington, R. E., Steiner, C. A., . . . Berry, D. J. (2015). Prevalence of total hip and knee replacement in the United States. JBJS, 97(17), 1386-1397.

Kumar, R. M., Rajesh, K., Haldar, S., Gupta, P., Murali, K., Roy, P., & Lahiri, D. (2019). Surface modification of CNT reinforced UHMWPE composite for sustained drug delivery. Journal of Drug Delivery Science and Technology, 52, 748-759.

Kumara, V., Tewaria, R. P., Pandeya, R., & Rawata, A. (2023). Triboinformatic Modeling of Wear in Total Knee Replacement Implants Using Machine Learning Algorithms. Journal of Materials, 1(3), 97-105.

Kurt, H. I., & Oduncuoglu, M. (2015). Application of a neural network model for prediction of wear properties of ultrahigh molecular weight polyethylene composites. International Journal of Polymer Science, 2015.

Kurtz, S. M. (2009). UHMWPE biomaterials handbook: ultra high molecular weight polyethylene in total joint replacement and medical devices: Academic Press.

Kurtz, S. M. (2016). The origins of UHMWPE in total hip arthroplasty. In UHMWPE biomaterials handbook (pp. 33-44): Elsevier.

Kurtz, S. M., Muratoglu, O. K., Evans, M., & Edidin, A. A. (1999). Advances in the processing, sterilization, and crosslinking of ultra-high molecular weight polyethylene for total joint arthroplasty. Biomaterials, 20(18), 1659-1688.

Lahiri, D., Hec, F., Thiesse, M., Durygin, A., Zhang, C., & Agarwal, A. (2014). Nanotribological behavior of graphene nanoplatelet reinforced ultra high molecular weight polyethylene composites. Tribology International, 70, 165-169.

Langhorn, J., Borjali, A., Hippensteel, E., Nelson, W., & Raeymaekers, B. (2018). Microtextured CoCrMo alloy for use in metal-on-polyethylene prosthetic joint bearings: Multi-directional wear and corrosion measurements. Tribology International, 124, 178-183.

Lapcikova, M., Slouf, M., Dybal, J., Zolotarevova, E., Entlicher, G., Pokorny, D., . . . Sosna, A. (2009). Nanometer size wear debris generated from ultra high molecular weight polyethylene in vivo. Wear, 266(1-2), 349-355.

Liu, B., Vu-Bac, N., Zhuang, X., Fu, X., & Rabczuk, T. (2022). Stochastic integrated machine learning based multiscale approach for the prediction of the thermal conductivity in carbon nanotube reinforced polymeric composites. Composites science and technology, 224, 109425.

Liu, J.-L., Zhu, Y.-Y., Wang, Q.-L., & Ge, S.-R. (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.

Liu, Y., & Sinha, S. K. (2013). Wear performances and wear mechanism study of bulk UHMWPE composites with nacre and CNT fillers and PFPE overcoat. Wear, 300(1-2), 44-54.

Liza, S., Haseeb, A., Masjuki, H. H., & Abbas, A. (2013). The Wear Behavior of Cross-Linked UHMWPE under Dry and Bovine Calf Serum–Lubricated Conditions. Tribology Transactions, 56(1), 130-140.

Luttjeboer, J. S., Bénard, M. R., Defoort, K. C., van Hellemondt, G. G., & Wymenga, A. B. (2016). Revision total knee arthroplasty for instability—outcome for different types of instability and implants. The Journal of arthroplasty, 31(12), 2672-2676.
Macuvele, D. L. P., Colla, G., Cesca, K., Ribeiro, L. F., da Costa, C. E., Nones, J., . . . Fiori, M. A. (2019). UHMWPE/HA biocomposite compatibilized by organophilic montmorillonite: An evaluation of the mechanical-tribological properties and its hemocompatibility and performance in simulated blood fluid. Materials Science and Engineering: C, 100, 411-423.
Mahesh, B. (2020). Machine learning algorithms-a review. International Journal of Science and Research (IJSR).[Internet], 9(1), 381-386.
Mahon, O. R., & Dunne, A. (2018). Disease-associated particulates and joint inflammation; mechanistic insights and potential therapeutic targets. Frontiers in Immunology, 9, 1145.
Malinov, S., Sha, W., & McKeown, J. (2001). Modelling the correlation between processing parameters and properties in titanium alloys using artificial neural network. Computational materials science, 21(3), 375-394.
Marques, P. A., Gonçalves, G., Singh, M. K., & Grácio, J. (2012). Graphene oxide and hydroxyapatite as fillers of polylactic acid nanocomposites: preparation and characterization. Journal of Nanoscience and Nanotechnology, 12(8), 6686-6692.
Martínez-Morlanes, M., Pascual, F., Guerin, G., & Puértolas, J. (2021). Influence of processing conditions on microstructural, mechanical and tribological properties of graphene nanoplatelet reinforced UHMWPE. Journal of the mechanical behavior of biomedical materials, 115, 104248.
Maskiewicz, V. K., Williams, P. A., Prates, S. J., Bowsher, J. G., & Clarke, I. C. (2010). Characterization of protein degradation in serum-based lubricants during simulation wear testing of metal-on-metal hip prostheses. Journal of Biomedical Materials Research Part B: Applied Biomaterials, 94(2), 429-440.
McGrath, L., Shardlow, D., Ingham, E., Andrews, M., Ivory, J., Stone, M., & Fisher, J. (2001). A retrieval study of capital hip prostheses with titanium alloy femoral stems. The Journal of Bone and Joint Surgery. British volume, 83(8), 1195-1201.
McKellop, H. A. (2007). The lexicon of polyethylene wear in artificial joints. Biomaterials, 28(34), 5049-5057.
McKellop, H. A., & D'Lima, D. (2008). How have wear testing and joint simulator studies helped to discriminate among materials and designs? JAAOS-Journal of the American Academy of Orthopaedic Surgeons, 16, S111-S119.
Mohammed, A. J., Mohammed, A. S., & Mohammed, A. S. (2023). Prediction of Tribological Properties of UHMWPE/SiC Polymer Composites Using Machine Learning Techniques. Polymers, 15(20), 4057.
Mohan, T., & Kanny, K. (2017). Tribological studies of nanoclay filled epoxy hybrid laminates. Tribology Transactions, 60(4), 681-692.

Mohanty, I., Bhattacharjee, D., & Datta, S. (2011). Designing cold rolled IF steel sheets with optimized tensile properties using ANN and GA. Computational materials science, 50(8), 2331-2337.
Myshkin, N., Petrokovets, M., & Kovalev, A. (2005). Tribology of polymers: Adhesion, friction, wear, and mass-transfer. Tribology International, 38(11-12), 910-921.

Nakanishi, Y., Nakashima, Y., Fujiwara, Y., Komohara, Y., Takeya, M., Miura, H., & Higaki, H. (2018). Influence of surface profile of Co-28Cr-6Mo alloy on wear behaviour of ultra-high molecular weight polyethylene used in artificial joint. Tribology International, 118, 538-546.
Naudie, D. D., & Rorabeck, C. H. (2004). Managing instability in total knee arthroplasty with constrained and linked implants. Instructional Course Lectures, 53, 207-215.
O'Brien, S. T., Bohm, E. R., Petrak, M. J., Wyss, U. P., & Brandt, J.-M. (2014). An energy dissipation and cross shear time dependent computational wear model for the analysis of polyethylene wear in total knee replacements. Journal of biomechanics, 47(5), 1127-1133.
Okeke, E. B., Louttit, C., Fry, C., Najafabadi, A. H., Han, K., Nemzek, J., & Moon, J. J. (2020). Inhibition of neutrophil elastase prevents neutrophil extracellular trap formation and rescues mice from endotoxic shock. Biomaterials, 238, 119836.
Oonishi, H. (1995). Long term clinical results of THR. Clinical results of THR of an alumina head with a cross-linked UHMWPE cup. Orthop Surg Traumatol, 38(11), 1255.
Oral, E., & Muratoglu, O. K. (2015). Crosslinked polyethylene. Materials For Total Joint Arthroplasty: Biotribology Of Potential Bearings, 133.
Ou, J., Wang, J., Liu, S., Mu, B., Ren, J., Wang, H., & Yang, S. (2010). Tribology study of reduced graphene oxide sheets on silicon substrate synthesized via covalent assembly. Langmuir, 26(20), 15830-15836.
Pajarinen, J., Cenni, E., Savarino, L., Gomez-Barrena, E., Tamaki, Y., Takagi, M., . . . Konttinen, Y. T. (2010). Profile of toll-like receptor–positive cells in septic and aseptic loosening of total hip arthroplasty implants. Journal of Biomedical Materials Research Part A: An Official Journal of The Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials, 94(1), 84-92.
Patil, N. A., Njuguna, J., & Kandasubramanian, B. (2020). UHMWPE for biomedical applications: Performance and functionalization. European Polymer Journal, 125, 109529.
Pramanik, S., Agarwal, A. K., & Rai, K. (2005). Chronology of total hip joint replacement and materials development. Trends in Biomaterials & Artificial Organs, 19(1), 15-26.
Puértolas, J., Martínez-Nogués, V., Martínez-Morlanes, M., Mariscal, M., Medel, F., López-Santos, C., & Yubero, F. (2010). Improved wear performance of ultra high molecular weight polyethylene coated with hydrogenated diamond like carbon. Wear, 269(5-6), 458-465.
Qiu, M., Chyr, A., Sanders, A. P., & Raeymaekers, B. (2014). Designing prosthetic knee joints with bio-inspired bearing surfaces. Tribology International, 77, 106-110.
Qiu, M., Minson, B. R., & Raeymaekers, B. (2013). The effect of texture shape on the friction coefficient and stiffness of gas-lubricated parallel slider bearings. Tribology International, 67, 278-288.
Ramakrishna, S., Mayer, J., Wintermantel, E., & Leong, K. W. (2001). Biomedical applications of polymer-composite materials: a review. Composites science and technology, 61(9), 1189-1224.

Reddy, S., Kumar, S., Varadarajan, K., Marpu, P., Gupta, T. K., & Choosri, M. (2018). Strain and damage-sensing performance of biocompatible smart CNT/UHMWPE nanocomposites. Materials Science and Engineering: C, 92, 957-968.
Renò, F., & Cannas, M. (2006). UHMWPE and vitamin E bioactivity: An emerging perspective. Biomaterials, 27(16), 3039-3043.

Rezaei, F., Yunus, R., & Ibrahim, N. (2009). Effect of fiber length on thermomechanical properties of short carbon fiber reinforced polypropylene composites. Materials & design, 30(2), 260-263.
Rodriguez-Galiano, V., Sanchez-Castillo, M., Chica-Olmo, M., & Chica-Rivas, M. (2015). Machine learning predictive models for mineral prospectivity: An evaluation of neural networks, random forest, regression trees and support vector machines. Ore Geology Reviews, 71, 804-818.
Rodriguez-Merchan, E. C. (2011). Instability following total knee arthroplasty. HSS Journal®, 7(3), 273-278.
Roman-Lopez, J., Correcher, V., Garcia-Guinea, J., Rivera, T., & Lozano, I. (2014). Thermal and electron stimulated luminescence of natural bones, commercial hydroxyapatite and collagen. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 120, 610-615.
Ruan, S., Gao, P., Yang, X. G., & Yu, T. (2003). Toughening high performance ultrahigh molecular weight polyethylene using multiwalled carbon nanotubes. Polymer, 44(19), 5643-5654.
Sadoghi, P., Liebensteiner, M., Agreiter, M., Leithner, A., Boehler, N., & Labek, G. (2013). Revision surgery after total joint arthroplasty: a complication-based analysis using worldwide arthroplasty registers. The Journal of arthroplasty, 28(8), 1329-1332.
Saikko, V. (2003). Effect of lubricant protein concentration on the wear of ultra-high molecular weight polyethylene sliding against a CoCr counterface. J. Trib., 125(3), 638-642.
Saikko, V. (2005). A hip wear simulator with 100 test stations. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 219(5), 309-318.
Saikko, V. (2019). Effect of serum dilution fluids on the wear of unirradiated and high dose gamma-irradiated, vitamin E stabilized UHMWPE. Wear, 430, 76-80.
Saikko, V., Morad, O., & Viitala, R. (2021). Effect of type and temperature of serum lubricant on VEXLPE wear and friction. Wear, 470, 203613.
Saikko, V., Morad, O., & Viitala, R. (2022). Effect of temperature on UHMWPE and VEXLPE friction and wear against CoCr in noncyclic tests. Wear, 490, 204190.
Salari, M., Mohseni Taromsari, S., Bagheri, R., & Faghihi Sani, M. A. (2019). Improved wear, mechanical, and biological behavior of UHMWPE-HAp-zirconia hybrid nanocomposites with a prospective application in total hip joint replacement. Journal of Materials Science, 54(5), 4259-4276.
Samad, M. A., & Sinha, S. K. (2011). Mechanical, thermal and tribological characterization of a UHMWPE film reinforced with carbon nanotubes coated on steel. Tribology International, 44(12), 1932-1941.
Santerre, J. P., Labow, R. S., & Boynton, E. L. (2000). The role of the macrophage in periprosthetic bone loss. Canadian Journal of Surgery, 43(3), 173.
Schwartz, C. J., Bahadur, S., & Mallapragada, S. K. (2007). Effect of crosslinking and Pt–Zr quasicrystal fillers on the mechanical properties and wear resistance of UHMWPE for use in artificial joints. Wear, 263(7-12), 1072-1080.
Selders, G. S., Fetz, A. E., Radic, M. Z., & Bowlin, G. L. (2017). An overview of the role of neutrophils in innate immunity, inflammation and host-biomaterial integration. Regenerative biomaterials, 4(1), 55-68.
Sharma, V., Chowdhury, S., Keshavan, N., & Basu, B. (2023). Six decades of UHMWPE in reconstructive surgery. International Materials Reviews, 68(1), 46-81.
Shen, G., Fang, F., & Kang, C. (2018). Tribological performance of bioimplants: a comprehensive review. Nanotechnology and Precision Engineering, 1(2), 107-122.

Steinbeck, M. J., Jablonowski, L. J., Parvizi, J., & Freeman, T. A. (2014). The role of oxidative stress in aseptic loosening of total hip arthroplasties. The Journal of arthroplasty, 29(4), 843-849.
Stewart, T. (2010). Tribology of artificial joints. Orthopaedics and Trauma, 24(6), 435-440.
Stoller, A. P., Johnson, T. S., Popoola, O. O., Humphrey, S. M., & Blanchard, C. R. (2011). Highly crosslinked polyethylene in posterior-stabilized total knee arthroplasty: in vitro performance evaluation of wear, delamination, and tibial post durability. The Journal of arthroplasty, 26(3), 483-491.
Suarez, J. C. M., & de Biasi, R. S. (2003). Effect of gamma irradiation on the ductile-to-brittle transition in ultra-high molecular weight polyethylene. Polymer Degradation and Stability, 82(2), 221-227.
Sun, X., Opulencia, M. J. C., Alexandrovich, T. P., Khan, A., Algarni, M., & Abdelrahman, A. (2022). Modeling and optimization of vegetable oil biodiesel production with heterogeneous nano catalytic process: Multi-layer perceptron, decision regression tree, and K-Nearest Neighbor methods. Environmental Technology & Innovation, 27, 102794.
Sundfeldt, M., V Carlsson, L., B Johansson, C., Thomsen, P., & Gretzer, C. (2006). Aseptic loosening, not only a question of wear: a review of different theories. Acta orthopaedica, 77(2), 177-197.
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.
Suñer, S., & Emami, N. (2014). Investigation of graphene oxide as reinforcement for orthopaedic applications. Tribology-Materials, Surfaces & Interfaces, 8(1), 1-6.
Tai, Z., Chen, Y., An, Y., Yan, X., & Xue, Q. (2012). Tribological behavior of UHMWPE reinforced with graphene oxide nanosheets. Tribology Letters, 46(1), 55-63.
Thongruang, W., Balik, C. M., & Spontak, R. J. (2002). Volume-exclusion effects in polyethylene blends filled with carbon black, graphite, or carbon fiber. Journal of Polymer Science Part B: Polymer Physics, 40(10), 1013-1025.
Uddin, M., & Zhang, L. (2013). Predicting the wear of hard-on-hard hip joint prostheses. Wear, 301(1-2), 192-200.
Verma, N., Keshri, A. K., Zafar, S., Prasad, A., & Pathak, H. (2022a). Comparative analysis on tribological and biological responses of UHMWPE-based composite and UV irradiated UHMWPE. Biotribology, 32, 100225.
Verma, N., Keshri, A. K., Zafar, S., Prasad, A., & Pathak, H. (2022b). Wear rate and biocompatibility of pre and post UV irradiated UHMWPE for tribo-pair in total knee replacement application. Journal of the mechanical behavior of biomedical materials, 135, 105436.
Verma, N., Pathak, H., Keshri, A. K., Prasad, A., & Zafar, S. (2022). Influence of UV exposure on mechanical behavior and cellular compatibility of nano-hydroxyapatite reinforced ultra-high molecular weight polyethylene. Materials Today Communications, 31, 103542.
Vinoth, A., Dey, S., & Datta, S. (2021). Designing UHMWPE hybrid composites using machine learning and metaheuristic algorithms. Composite Structures, 267, 113898.
Vipin Kumar, A. R. a., & Tewari, R. P. (2023). Prediction of Wear in Total Knee Replacement Implants Using Artificial Neural Network. International Journal of Biomedical Engineering and Technology, Accepted.
Visco, A., Yousef, S., Galtieri, G., Nocita, D., Pistone, A., & Njuguna, J. (2016). Thermal, mechanical and rheological behaviors of nanocomposites based on UHMWPE/paraffin oil/carbon nanofiller obtained by using different dispersion techniques. Jom, 68(4), 1078-1089.

Wang, A. (2001). A unified theory of wear for ultra-high molecular weight polyethylene in multi-directional sliding. Wear, 248(1-2), 38-47.
Wang, A., Essner, A., & Schmidig, G. (2004). The effects of lubricant composition on in vitro wear testing of polymeric acetabular components. Journal of Biomedical Materials Research Part B: Applied Biomaterials: An Official Journal of The Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials, 68(1), 45-52.
Wang, A., Schmidig, G., Essner, A., & Serekian, P. (2000). Effect of lubricant protein composition on the outcome of hip joint simulator testing. Paper presented at the Transactions of the 46th Annual Meeting of the Orthopaedic Research Society, Orlando, Florida, USA.
Wang, J., Chen, B., Liu, N., Han, G., & Yan, F. (2014). Combined effects of fiber/matrix interface and water absorption on the tribological behaviors of water-lubricated polytetrafluoroethylene-based composites reinforced with carbon and basalt fibers. Composites Part A: Applied Science and Manufacturing, 59, 85-92.
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.
Weeden, S. H., & Schmidt, R. H. (2007). The use of tantalum porous metal implants for Paprosky 3A and 3B defects. The Journal of arthroplasty, 22(6), 151-155.
Wicaksono, F., Ismail, R., & Jamari, J. (2018). A study of the compression molding method for manufacturing a UHMWPE liner. Paper presented at the IOP Conference Series: Materials Science and Engineering.
Wilches, L., Uribe, J., & Toro, A. (2008). Wear of materials used for artificial joints in total hip replacements. Wear, 265(1-2), 143-149.
Willing, R., & Kim, I. Y. (2009). Three dimensional shape optimization of total knee replacements for reduced wear. Structural and Multidisciplinary Optimization, 38(4), 405-414.
Wolford, L., Pitta, M., Reiche-Fischel, O., & Franco, P. (2003). TMJ Concepts/Techmedica custom-made TMJ total joint prosthesis: 5-year follow-up study. International journal of oral and maxillofacial surgery, 32(3), 268-274.
Wu, X., Zhang, J., Wu, C., Wang, G., & Jiang, P. (2013). Study on tribological properties of UHMWPE irradiated by electron beam with TMPTMA and TPGDA as crosslinking agents. Wear, 297(1-2), 742-751.
Xiong, L., Xiong, D., Yang, Y., & Jin, J. (2011). Friction, wear, and tensile properties of vacuum hot pressing crosslinked UHMWPE/nano-HAP composites. Journal of Biomedical Materials Research Part B: Applied Biomaterials, 98(1), 127-138.
Xue, Y., Wu, W., Jacobs, O., & Schädel, B. (2006). Tribological behaviour of UHMWPE/HDPE blends reinforced with multi-wall carbon nanotubes. Polymer Testing, 25(2), 221-229.

Yang, D., Qu, S., Huang, J., Cai, Z., & Zhou, Z. (2012). Characterization of alendronate sodium-loaded UHMWPE for anti-osteolysis in orthopedic applications. Materials Science and Engineering: C, 32(2), 83-91.
Yao, J., Laurent, M., Gilbertson, L., Jacobs, J., & Crowninshield, R. (2001). Viscosity of fresh and thermally degraded bovine calf serum and its implications for in-vitro wear testing. Paper presented at the Society for Biomaterials 27th Annual Meeting Transactions.

Yousef, S., Visco, A., Galtieri, G., Nocita, D., & Espro, C. (2017). Wear behaviour of UHMWPE reinforced by carbon nanofiller and paraffin oil for joint replacement. Materials Science and Engineering: C, 73, 234-244.

Zhang, Y., Hou, C., Yu, S., Xiao, J., Zhang, Z., Zhai, Q., . . . Lehto, M. (2012). IRAK-M in macrophages around septically and aseptically loosened hip implants. Journal of Biomedical Materials Research Part A, 100(1), 261-268.

Zhao, D., Sakoda, H., Sawyer, W. G., Banks, S. A., & Fregly, B. J. (2008). Predicting knee replacement damage in a simulator machine using a computational model with a consistent wear factor. Journal of biomechanical engineering, 130(1).

Zoo, Y.-S., An, J.-W., Lim, D.-P., & Lim, D.-S. (2004). Effect of carbon nanotube addition on tribological behavior of UHMWPE. Tribology Letters, 16(4), 305-309.