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REVIEW PAPER

Wear Performance of UHMWPE and PCU Artificial Disc Materials

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Abstract Artificial disc replacements are used in total disc replacement (TDR) procedures as an alternative to lumbar spinal fusion, to treat degenerative disc diseases (DDD). Artificial lumbar disc devices have a core that typically uses ultra-high molecular weight polyethylene (UHMWPE), but in recent times, a new type of polymer, polycarbonate urethane (PCU), has been proposed and is subjected to many ongoing researches for commercial use. These two polymers by virtue of their biocompatibility, chemical stability and load bearing capabilities have become good alternatives to closely replicate the functions of cartilaginous natural intervertebral discs. Despite the popularity and need of artificial lumbar discs, commercial discs rarely last more than two decades. The main reason behind failure is osteolysis resulting from wear loss of the polymer due to constant friction. Improving the wear properties without harming other significant mechanical properties has been an important area of research interest of modern arthroplasty. Two popular methods of bettering wear rate are cross-linking and reinforcing. This paper attempts to review the wear properties of both, UHMWPE and PCU, from a plethora of available literature.

Keywords Artificial disc replacement · UHMWPE · PCU · Wear

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Introduction

Modern day lifestyle demand a lot of stress upon our bodies and one of its effects can be evidently seen on our spine. Lower back problems (LBP) are one of the most common problems, almost 80 per cent of the world population experiences it at least once in their lifetimes [1]. Over 256 million people globally suffer of degenerative disc diseases (DDD) and LBP every year. This has increased the market scope as well as research potential upon this field. TDR is used as an alternative to spinal fusion surgery; the latter aims at treating DDD by erasing the source of pain after eliminating spinal motion through implantations, the former aims at eradicating the pain while preserving the spinal motion through replacing the natural disc with an artificial one. An artificial disc market study reported that market size of artificial discs, which was 1.6 billion USD in the year 2019, is predicted to be around USD 5.6 billion by the year 2026 [2]. The polymeric core of of artificial discs uses polymers like UHMWPE, PCU, PUPC, SPCU and PEEK. The end plates are often metal alloys of Ti, Co-Cr and stainless steel. Some commercially available discs are: Kineflex-L (SpinalMotion, Inc.), Flexicore (Stryker) I, XL TDR (NuVasive)I, Maverick (Medtronic)I and Freedom (AxioMed) [3].

Artificial discs typically have three parts, upper and lower endplates and a sliding core in between them [4, 5]. The core has used UHMWPE as a material for decades and in recent times. UHMWPE, because of its excellent properties of biocompatibility, chemical inertness, impact resistance, abrasion resistance, low coefficient of friction and load bearing capabilities, has found wide usage as an orthopaedic implant since 1962 [6]. Almost two decades later in the early 1980s, Schellnack and Buttner-Janz developed the first lumbar disc to use UHMWPE as the sliding core along with two metallic plates: SB Charité I [7]. Now, unlike spinal fusion, artificial discs have scope for motion, which results in friction; the friction causes material wear, which in turn causes inflammatory reaction and osteolysis [8]. Osteolysis is the major cause behind disc failures. PEEK (polyether ether ketone) is one of the polymers that was first proposed for spinal usage some two decades ago; it is used in both spinal fusion and disc replacement surgeries [9]. PEEK is a short fibre semi-crystalline thermoplastic polymer with excellent mechanical properties and modulus of elasticity, chemical inertness, wear properties and biocompatibility. It makes a good core material but also the less rigidity compared to metal rods, make it suitable in spinal fusion [10]. Apart from this Cobalt-Chrome too finds a usage in prosthetics because of high specific strength. The alloy used in implantations typically uses 5–7% molybdenum, Co–Cr–Mo [5]. Some commercially available discs like Kineflex-L (SpinalMotion, Inc.) use a Co–Cr core [11]. Alloys of titanium and stainless steel (SS-316L) too finds wide usage in bio-implantations; these alloys although considerably less biocompatible when compared to polymers show better mechanical properties. SS-316L is cheaper than Ti alloys [12, 13]. Through the decades, however, despite these alternatives, UHMWPE is still considered the gold standard for artificial lumbar disc core material.

In recent times, the search for more compliant materials as an alternative to UHMWPE has led us into the study of PCU. The major setback with UHMWPE is its wear rate due to friction, causing high debris concentration resulting in osteolysis; hence, disc failure. Due to a combination of elasto-hydrodynamic lubrication (EHL) and micro-elasto-hydrodynamic lubrication (lEHL), a fluid film is developed in natural synovial joints that reduces friction and maintains a low wear rate for decades [14]. By virtue of its mechanical and tribological properties that are comparable to natural cartilage and low particle generation, PCU has excellent potential to be a better material for artificial lumbar discs [14, 15]. Recently, in the year 2019, FDA approved M6 (Spinal Kinetics, Sunnyvale, CA), a non-articulating disc implant that integrates PCU as the core, for commercial use. So, the long-term results are yet to be seen.

Owing to its nature of biocompatibility and satisfactory wear properties, UHMWPE is a suitable material for manufacture of hip endoprostheses [16]. But, its applications don't only limit to bio-implants. The discovery of a new fibrillar structure in DSM laboratory, back in the 1960s, led the foundation of development of high-strength UHMWPE fibres [17]. Because of its high tensile strength and low density, it finds usage in ballistic applications as well. The typical tensile strength and density values of commercial UHMWPE fibres are 3.6 GPa and 960 kg/m^3 [18]. PCUs are used as hard-on-soft bearing to imitate the natural cartilage in hip arthrolplasty, meniscus in knee arthroplasty and in artificial invertebral discs. Apart from these, PCU is incorporated in several spinal posterior dynamic stabilisation devices (PDSD) to achieve better flexibility and viscous damping in the device, such as the Dynesys® (Zimmer Spine, Inc., USA), the Flex + 2® (Spine Vision, S.A., Belgium), the TDX® (Orthofix, Inc.) or the Transition® (Globus Medical, Inc.), to name a few. [19].

In this article, review of available literature on the wear and mechanical properties of the two most important polymers: UHMWPE and PCU, were carried out. The commercially available artificial devices and their materials were given in Table 1.

Core Materials

UHMWPE

The morphology and structure of any material defines its properties and hence is of utmost importance for better understanding of UHMWPE. UHMWPE is a subset of thermosetting plastic, a polyolefin fibre, i.e. a long synthetic polymer chain largely composed of olefin units. The repeating unit here is $[C_2H_4]_n$ where n denotes the degree of polymerization.The UHMWPE used for orthopaedic implants has a degree of polymerization between 71,000 and 214,000 and a molecular mass of 2–6 million g/mole [22].

Structurally, UHMWPE exists in two phases: crystalline and amorphous [23]. The crystalline part exists as long range ordered sheetlike molecular structures (lamellae) with thickness of about 10–50 nm and length range of about 10–50 µm [6]. And, in the amorphous regions, the lamellae lack any order. The long chains of repeating units giving it a very heavy mass manifest into several unique properties that make UHMWPE so useful to us. UHMWPE has the highest abrasion resistance and impact strength in comparison with other commercial plastics, making it a choice for ballistic vests as well [24]. Other than these, UHMWPE's excellent biocompatibility, self-lubrication, low moisture absorption and coefficient of friction make it one of the best choices for biomaterial implants [25]. The UHMWPE commercially used in the disc SB Charite III is of the approved standard ISO 5834/11 and ASTM F 648–83 [26]. The raw material used of this standard is compression-molded GUR 1020 from Poly HI Solidur [27]

Despite being the best choice till date, UHMWPE suffers from a significant setback of generating wear debris throughout the years of its dynamic usage, which reduces its life to 15–20 years [28]. A lot of studies have been done

Table 1 Examples of some commercial discs

Bearing surfaces	Materials	Commercial Device name	References
Metal on Metal	CoCr-CoCr	Maverick	[11, 20]
		XL-TDR	
Metal on Polymer	DLC coated Ti-UHMWPE	Baguera	[4, 11]
	CoCr-UHMWPE	Mobidisc	
Polymer on Polymer	PEEK-PEEK	Nubac	[21]
One piece	Ti plates; silicone PU-PC core	Freedom	[11]
	Ti plates; elastomer core	eDisc	[11]

on the wear properties of UHMWPE and several reinforcements have been experimented with. The review of some of the reinforcements is discussed.

Wear properties of pure UHMWPE

This section reviews the mechanical and wear properties of pure UHMWPE. The polymer has very long chains of polyethylene, primarily bonded by VanDer Waals forces. Although the atom to atom Van Der Waals bond is weak in nature, but the long length of the molecular chains provides opportunities for large numbers of overlapping, which, in turn, increases the strength of the structure allowing it to endure large shear forces molecule to molecule [22].

Ram extrusion and compression moulding are primarily used commercially to manufacture UHMWPE. The later being the oldest method, since 1950s [29]. The significance of the study of pure UHMWPE lies in the fact that despite its decades long history and search for its alternatives, UHMWPE still is the most important polymer for bio-implantations. It has been found that oxidative degradation is one of the main reasons behind failure of UHMWPE. It leads to reduction of abrasive wear resistance, which leads to more debris generation during sliding, resulting in osteolysis: the main cause behind failures of lumbar discs [30–33].

In this section, a review of the wear and mechanical properties of two most commonly used grades of UHMWPE in orthopaedics are GUR 1020 and GUR 1050, defined as per BS ISO 5834–2 2011, are done [34]. The mechanical properties of GUR 1020 and 1050 are shown in Table 2.

Now, as discussed that the two methods of manufacturing UHMWPE commercially are Ram extrusion method and compression moulding. Table 3 shows the effects of the two different processes on mechanical properties of the UHMWPE.

Wear properties cross-linking UHMWPE

Cross-linking a polymer is changing the bond alignments adjacently. Usually, it is done through three methods: radiation induced cross-linking, chemical induced cross-linking and silane compound induced cross-linking. The wear rates of GUR 1020 and GUR 1050 is given in Table 4.

1) Radiation induced cross-linking Two important structural changes occur during cross-linking UHMWPE using ionizing radiation: first, chain scission (breakage of C–C bond) of the tie molecules and second, bond formation with the adjacent free radicals. The goal of cross-linking a polymer using an ionizing radiation is to reduce the wear rate of the polymer. But, one of its prime disadvantages is that it leaves behind residual free radicals which can react to deteriorate other significant mechanical properties [40].

The problem with UHMWPE is, despite the creation of large numbers of free radicals, the carbon atom to carbon atom distance at the structural level is too far for a bond to develop (0.41 nm) and lattice too is too rigid at room temperatures to permit typical C-C interchain bonds

Table 2 Mechanical properties of GUR 1020 and 1050

Sample	Tensile yield strength (kJ/m^2)	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Crystallinity (%)	References
GUR 1020	24.6	63	23 ± 1	64.3	[35, 36]
GUR 1050	21.7	50	23 ± 2	63.4	[35, 36]

Table 3 The data were taken from [37]

Tests	Extruded GUR 1020	Moulded GUR 1020	Extruded GUR 1050	Moulded GUR 1050
Tensile Yield (Mpa)	22.3	21.9	21.5	21
Ultimate Tensile Strength (Mpa)	53.7	51.1	50.7	46.8
Elongation to failure (%)	452	440	395	373

Table 4 This table reviews the wear rates of GUR 1020 and GUR 1050 samples

Sample (Gamma Irradiation (kGy))	Wear rate ± standard deviation (mg/Mc)	Wear factor ± standard deviation × 10^{-6} (mm^3 Nm)	References
GUR 1020 (0)	9.4 ± 1.2	3.92 ± 0.55	[35]
GUR 1050 (0)	8.5 ± 1.1	3.64 ± .39	[35]
GUR 1020 (0)	1.70 ± 0.63	1.2 ± 0.45	[38]
GUR 1050 (0)	7.87 ± 2.86	2.2 ± 0.8	[39]

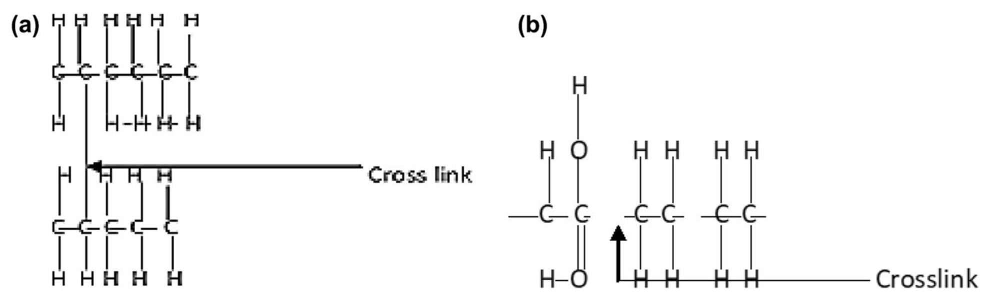

Fig. 1 **a** Chain scission of tie molecules, **b** bond formation between free radicals adjacently [42]

(0.154 nm) [41]. The chemical formulation of the crosslink UHMWPE is given in Fig. 1.

2) Chemically induced cross-linking. In chemically induced cross-linking, as the name suggests, chemicals that generate free radicals, or free radical generating chemicals (FRGC), are used. The process of cross-linking takes place at the molten state when the FRGC decomposes to release free radicals. These radicals extract the hydrogen atoms leaving reactive sites behind for C–C bonds to form adjacently. This might suggest that it is necessary to select a FRGC which decomposes at the melting temperature of UHMWPE. For UHMWPE, currently an organic peroxide with three of these most preferred formulations is used: (i) 2,5-dimethyl-2,5-bis(tert-butylperoxy) 3-hexene (Lupersol 130; Atochem, Inc., Philadelphia, PA, USA); (ii) dicumyl peroxide (Lupersol 101; Atochem, Inc.); and (iii) 2,5-dimethyl-2,5-di(t-butylperoxy)-hexane (Varox 130).

3) Silane compound induced cross-linking: In this method, cross-linking is achieved by grafting a silane compound that contains a vinyl or hydrolyzable group onto a polymer at the molten state. Organic peroxides are used as initiators. Followed by a shaping the material into the final product using a suitable moulding process. Post this, cross-linking is achieved by water or water vapours at a high temperature. In the final stage, to make silane hydrolyze into Si–OH and then by condensation of Si–OH to form the Si–O–Si linkage between the polymer chains, water acts as a cross-linking agent.

A lot of work has been done on polyolefins like HDPE [43, 44], LDPE [45], LLDPE [46]. However, the cost and other shortcomings of the previous two steps have made silane induced cross-linking a preferable option in recent times. The properties of UHMWPE and pin on disc wear rates of crosslinked UHMWPE were given in the Tables 5 and 6 respectively.

Wear properties of reinforced UHMWPE

Reinforcing UHMWPE is a promising method of enhancing the properties of it. It is popularly reinforced with carbon nanotubes [52], graphene [53], filling of silver [54], Zn/Ti/Hf [55], alumina nanoparticles [56]. As the review

Table 5 This table lists down many UHMWPE samples and their YS, UTS, melting point and crystallinity percentage

Resin used	YS (Mpa)	UTS (Mpa)	T_M (°C)	X(%)	References
GUR 4150 Ram extruded (IMS)	18	14	126	38	Muratoglu et al. [47]
GUR 4150 (CISM)	20	29	137	48	Muratoglu et al. [47]
GUR 1050 (WIAM)	20 ± 0	30 ± 1	137	45 ± 0.4	Muratoglu et al. [47]
GUR 1050 (G-PRX)	18	3	126	40	Muratoglu et al. [47]
peroxidecrosslinked Himont 1900 (H-PRX)	NA	NA	17	46	Muratoglu et al. [47]
Marathon (DePuy/J and J) (Gamma irradiated)	21 ± 1.5	56 ± 5.7	NA	NA	Baena et al. [28]
Compression-molded GUR 1050	22.0; 24.1[d]	35.8; 25.5[d]	140; 140[b]	60; 59[b]	King et al. [48]
GUR 415	NA	49.0	128.1[d]; 129.2[e]	43.4[d]; 49.0[e]	Oonishi et al. [49] Shen et al. [50]

YS: yield strength; UTS: ultimate tensile strength; T_M: melting temperature; X(%): crystallinity percentage; [b]After accelerated ageing (heated in O2 gas at 373C and 0.58 MPa for 70 d). [d]Beforeγ (gamma) irradiation of the specimen. [e]Afterγ irradiation of the specimen in air (up to 3.4 Mrad)

Table 6 POD rates of various cross-linked samples [51]

Sample	Condition	Crystallinity (%)	POD Wear rate WR (g/MC)
CISM 50	Absorbed ration dose level (kGy): 50	48.5 ± 0.7	4.8 ± 0.7
G-PRX-0.3	Peroxide content, wt%:.30	43 ± 0.4	3.3 ± 0.54
H-PRX-0.3	Peroxide content, wt%:.30	50 ± 0.5	6.93 ± 1.13

here is about primarily wear properties, UHMWPE's inertness poses one unique complication. The chemical inertness of this polymer is one of the reasons making it fit for being a bio-implantation material, but this inertness restricts the scope of its tribological enhancement. For example, it is a well established fact that increase in crystallinity reduces wear rate; an inversely proportional relation. Maximum crystallinity can be achieved in fibres with a fibrillar structure, which in turn can be achieved through methods of gel spinning and followed by orientational drawing [57]. But such methods are not possible because of the inertness of UHMWPE. However, this problem has been dealt with a few interesting solutions: one, self-reinforcing composites and second is surface treatment methods.

In 1975, Capiati and Porter presented a unique method to reinforce polymeric material. The idea was to prepare composites with reinforcements and matrix of same polymer but of different morphologies. Nor did it just enhance material properties but also had numerous other advantages of possessing less density and being easily recyclable (since one will not need to separate the materials as they are the same polymer) [58]. The other method is of surface treatments including nitrogen plasma [59], nitrogen ion implantation [60], fast atom beams [61], oxygen-plasma treatment [62], etc.

The table below reviews some reinforcements used on UHMWPE samples and their corresponding effects on wear and other mechanical properties. The fillers used with UHMWPE is given in Table 7 and the crystallinity of self reinforced composite of UHMWPE is given in Table 8.

Polycarbonate Urethane (PCU)

The limited life of UHMWPE has led research into finding alternatives for it. Commercially UHMWPE is still the material of choice for many artificial prostheses, but polyurethanes have also been of interest to researchers since almost five decades now [63]. Polyurethanes, because of a combination of excellent physical properties and biocompatibility, have the potential of replacing UHMWPE. Just like polymers, polyurethanes too have their great tribological properties by virtue of their microstructure; the unique microphase separated morphology between hard and soft segments and nature of the chain extender [64]. Zhu et al. have found the increase in the hard segment influences the surface roughness, decreasing the latter while increasing the degree of crystallization and multiphase separation.The polyfunctionalisocyanate, of the hard segments can be divided into aliphatic, aromatic, polycyclic, or cycloaliphatic [65]. The mechanical properties of the polymer are dependent on the diisocyanate, microdiols, the chain extender, and especially the urethane linkages of the hard segments [66–69]. Commercial Bionate 80A (PCU) has soft segment sofpoly(hexamethylene carbonate) (PHMC) and a hard-to-soft segment ratio of 35/65 [70]. It

Table 7 Some popularly used fillers and their effects on mechanical properties and effects on wear rate Baena et al. [28]

Fillers	Percentage of inclusion	Improved properties	Reduction in wear rate
Carbon nanofibers (CNF)	0.5–5%	Tensile strength	56–58%
Carbon nanotube (CNTs)	0.1–5%	Tensile strength Young's modulus Toughness	26–86%
Graphene	0.1–1.0%	Lubrication, tensile strength Yield strength Reducing friction coefficient	2.5–4.5 times (depending on load)
Hard particles	10–20%	Bearing loading capacity	36–60%

Table 8 Crystallinity of self-reinforced composite (SRC) of UHMWPE at different pressure and temperature conditions. [58]

Hot Compaction Temperature, °C	Crystallinity (%) and 25 Mpa	Crystallinity (%) and 50 Mpa
155	92.0 ± 1.1	94.0 ± 0.9
160	91.0 ± 1.3	93.0 ± 1.2
165	87.0 ± 0.9	89.0 ± 1.3
170	69.0 ± 1.2	84.0 ± 1.7

has been found that polycarbonate softer segments are more biostable than comparable PEUs [71].

To fit in for specific purposes such as hip or lumbar implants, polyurethanes have been synthesized for better wear properties. PCU is already being used for some biomedical applications like heart valve and vascular grafts because of its biostability and biocompatibility [72–75]. Apart from these, PCU has also been investigated for knee prosthesis [76], meniscus [77], hip prosthesis [15] and most importantly, spinal implant [78].

One of the main advantages of PCU over UHMWPE is that the former has a greater oxidative stability, and as already mentioned that UHMWPE's poor oxidative stability is one of the main causes behind its failure [79].

PCU's elongation at break ranges over 1100 to 1450% and Young's Modulus 2.6 to 4.8 MPa [80]. It also acts as a preferable alternative to usual polyurethanes. The main factors behind degradation of polyurethans (PUs) are hydrolysis, environmental stress cracking (ESC), metal ion oxidation (MIO) and calcification. Commercial PCUs have shown outsanding resistance to these degrading mechanisms, indicating of applications in more robust conditions [81].

The softer nature of PCU poses a challenge in its usage in dental or meniscus implants but those hurdles are overcome by reinforcing. Here is review of some of the mechanical and wear properties of pure and reinforced PCU.

Wear properties of pure polycarbonate urethane (PCUs)

In the following table, listed down are the mechanical properties of PCU samples Bionate 75D, 80A and 90A. Bionate 90A is slightly heavier than 80A, as the former has a molecular weight of 253 kg/mole and the latter weighs 243 kg/mole [82].

$$\text{Wear rate} = \partial w(t)/\partial t \quad (1)$$

where w is the weight of the sample

Kanca et al. [83] investigated the in vitro wear performance of PCU 80A discs, Bionate I and II on two configurations, first being condyles articulating against the PCU discs. And the second configuration was a PCU pin on a cartilage surface. The investigation showed that PCU is a good candidate for use in hemiarthroplasty components. Also, Bionate® II showed better tribological performance, suggesting one can opt it over Bionate I for hemiarthroplasty designs. Neukamp et al. [84] conducted tests with PCU spacers to predict its use in spinal implantations and have found satisfactory results to see the potential use of its extensive usage. The mechanical properties and wear rate of PCU were given in Tables 9 and 10 respectively.

Wear properties of reinforced PCU

One problem with PCU is its softer nature in comparison with UHMWPE. And this forms a barrier in its usage as implants in dental and meniscus replacement surgeries, where the requirement is of a tougher substitute. But, studies have shown the possibility of reinforcing PCU samples with UHMWPE fibres [86].

Inyang et al. have impregnated PCU matrix with UHMWPE fibres and observed a 227% increment in its tensile modulus, alongside a slight decrease in density. The elastic modulus of the composite is 126,000 Mpa [85].

Table 9 Mechanical properties of some PCU samples

Sample	Tear Strength (kN/m)	Ultimate Tensile Strength (MPa)	Melting temperature (°C)	Elongation at break (%)	References
80A	64.90	46.64	–	531	[85]
90A	96.40	55.11	–	406	
75D	–	21.55	–	352.06 ± 0.33	[84]

For the wear rate of PCU Bionate 80A, Elsner et al. have found the Metal on PCU (moPCU) wear rate. The formula they used is:

Table 10 Wear rate and wear volume of Metal on Polymer (Bionate 80A)

Sample	Wear rate (particles Mc^{-1})	Wear volume (mm^3 Mc^{-1})	References
moPCU (Bionate 80A)	10^6	5–11	[14]

Geary et al. experimented on Bionate 75D, addition of carbon fibres have increased the ultimate tensile strength from 21.55 to 38.84 Mpa, and 80% increase. And a 74% decrease in ultimate elongation. Also, in addition to 20% hydroxyapatite filler, there was 22% reduction in UTS and 10% reduction in ultimate elongation [84].

Discussion

Relation Between Crystallinity and Wear Performance of an UHMWPE

As discussed earlier, UHMWPE has two regions: crystalline and amorphous. Also, it has been mentioned how the microstructure of the polymer plays an important role in shaping its properties. The wear properties of a polymer are dependent on micro-structural properties like crystallinity [87]. Karuppiah et al. [88] performed tests to find a relationship between crystallinity of UHMWPE and its wear rate. The results show that increase in crystallinity reduces wear rate. The friction coefficients and wear measurements as a function of UHMWPE crystallinity is given in Table 11.

The above mentioned table reinstates the point that increase in crystallinity reduces wear rate and also other critical parameters like scratch depth, scratch width, etc. This is also in accordance another test conducted that shows greater crystallinity results in heightened wear resistance and lower friction of UHMWPE samples [90]. Crystalline materials have finer microstructure, in comparison with amorphous materials. And hence, during relative motion, in vivo, loss due to friction will reduce with increased crystallinity. It appears that crystallinity is an important deciding factor for all polymers aimed at reducing wear.

Relationship Between Mechanical Properties and Wear Rate

As mentioned earlier, often in attempts to reduce wear rate by cross-linking, other important mechanical properties are

Table 11 Summary of friction coefficients and wear measurements as a function of UHMWPE crystallinity [89]. Here, HC-PE has percentage crystallinity of 55.1 and LC-PE, of 45.6

Sample	Microscale coefficient of friction[a](before damage)	Microscale coefficient of friction[a](after damage)	Interfacial shear strength[b] (MPa)	β[b]	Wear depth[c] (μm)	Wear width[c] (μm)	Scratch depth[d](μm)	Scratch width[d](μm)	Scratch depth[e](nm)
HC-PE	0.28 ± 0.02	0.15 ± 0.02	8.27	0.0098	0.12 ± 0.030	85.0 ± 5.9	0.46 ± 0.01	85.2 ± .01	3.98 ± 0.99
LC-PE	0.39 ± 0.03	0.22 ± 0.01	7.13	0.036	0.21 ± 0.016	113.5 ± 9.3	0.52 ± 0.01	102.3 ± 0.01	6.55 ± 0.37

[a]Measured using a Si3N4 probe on the microtribometer over a normal load range of 0–180 mN

[b](according to DMT contact mechanics) to AFM data

[c]Measured using a Si3N4 probe on the microtribometer for 1000 reciprocating, 20 mm cycles at an applied load of 125 mN

[d]Abrasive wear using a diamond probe on the tribometer for a 0–750 mN ramped-load scratch test. Depth measurements shown represent those at maximum load, 750 mN

[e] Measured using AFM at a normal load of 80 nN and 40 cycles

affected. This section will discuss about the relation between the wear rate of UHMWPE and PCU and some of the important mechanical properties. Works of Oberle [89] and Dreschar [91] suggest that wear rates of polymers are inversely proportional to H/E ratio, where H is the indentation hardness and E is the modulus of elasticity. Hence, lower hardness values and higher elasticity will give us lower wear. So, higher plastic deformation will imply higher wear.

The principle cause of wear in artificial lumbar discs is abrasive wear. In case of abrasive wear, where the UHMWPE/PCU material moves against endplates to generate debris, polymer's wear rate is directly proportional to μ/HS€, or:

$$W.R \propto \frac{\mu}{\mathrm{HS}€} \tag{2}$$

where *W.R* is the wear rate, μ is the coefficient of friction H: indentation hardness, S: breakingstrength and € is elongation [92]. There appears to be a positive relationship between key mechanical properties and wear rate.

Affects of Cross-Linking and Reinforcements on Wear rate

Vardhan et al. [93] conducted various tests (tensile, compression and wear) to find a relation between CNT filled UHMWPE and pure UHMWPE's wear rate. The results showed that for addition of 5% CNT in pure UHMWPE can reduce the wear rate by 73% while enhancing its tensile strength. The various other tests and their results mentioned in the above sections show that cross-linking of a polymer (UHMWPE and PCU) shows positive results in terms of wear performance. However, composites have shown even better results than cross-linked polymers, i.e. adding a suitable reinforcement like graphene reduces not only the wear rate but also enhances other key mechanical properties. It is clear that UHMWPE has been on focus significantly more than PCU in terms of research for wear and mechanical properties. And hence, literature on UHMWPE is more abundantly available when compared to PCU.

Gupta et al. have tested the wear rates of UHMWPE and PCU buffers against cobalt alloy femoral heads and found that PCU, softer material than UHMWPE, to be having significantly lower wear rate than UHMWPE. The wear rate of UHMWPE is around 100 mm^3/ Mc, where as for PCU's the wear rates is 25 mm^3/ Mc. And as already established, cross-linking UHMWPE reduces wear rate, but still PCU had 24% lesser wear rate in comparison with cross-linked UHMWPE [94]. One other potential advantage of PCU over UHMWPE is, the latter, both cross-linked and pure shows almost equivalent biological activity. However, in comparison with this, PCU shows less inflammatory reaction to preprosthetic tissues and bones. [88, 95].

It does give us an indication that PCU might become a significant choice of material for lumbar discs in near future.

Comparison of Wear Performances of MoM and MoP Discs

Metal on Metal artificial discs have been commercially available for lumbar, cervical and hip implants. MoM implants have an advantage on theory with regards to aseptic loosening concerned with polymer based implants; but follow-up studies have shown several other complications that lead to early failure, like osteolysis, formation of pseudo tumours on the soft tissues and inflammatory reaction with metal ions that enter circulation [96]. The concept of MoP had to be introduced because of the fast failures of early MoM plates. Polyethylene, due to large chains of carbon, gave it the structural strength as well as the inert characteristic [97]. However, later developments of MoM implants with better machining have led to more durability. A MoP that is conventionally used has a 50 per cent failure rate among younger patients, approximately while MoM have survived for longer periods [98, 99]. MoM implants can have larger surface areas of femoral heads that allow greater mobility, but, as discussed earlier the production of metal ions because of wear can have severely harmful effects on a human body and hence is less advisable compared to polymers [100]. A computational study done to compare the wear of a TDR using metal on polymer and metal on metal discs showed not much significant difference in linear wear; however, in terms of volumetric wear, the polymeric trough showed 1.8 times lesser wear compared to the metallic trough [101].

The studies done by Marichamy et al. on the vibrating wear of synthesized duplex brass metal matrix using a tribometer. The input parameters were temperature, normal force and speed and the output being wear rate. The results show an increase in wear along with increase in temperature, normal force and speed- speed being the most significant influencing factor and temperature being the second [102].

Another study was done by Kumar et al. on the wear behaviour of carbon nanotubes induced silicon metal using a pin-on-disc apparatus. The presence of CNT lowered the coefficient of friction considerably. The test results show that an increase on sliding distance and load increases wear. Sliding distance is the primary factor of influence and sliding distance the secondary [103].

Conclusion

A review of literature available on the wear performances of two commercially used artificial disc materials, UHMWPE and PCU, has been carried out. UHMWPE, although have been the first for more than five decades, suffers from the problem of rapid wear debris generation that limits its lifetime. Softer polyurethane materials are gaining increasing popularity for hard on soft bearing and PCU, because of its better oxidative stability and wear properties, has the potential of being the better alternative.

The article has reviewed that UHMWPE's wear rate improves with cross-linking and reinforcements. The latter shows better results than cross-linking. Also, there appears to be a strong co-relation between crystallinity and mechanical properties with the wear rate of the polymers. The wear rate seems to decrease with improvement in the two aspects.

Polycarbonate urethanes show excellent wear properties in comparison with UHMWPE and cross-linked UHMWPE. Also, reinforcements like CNT and carbon fibres significantly increases its tensile strength. The soft, more cartilage like surface, lower wear rate, superior oxidative stability and biostability seems to solves the problem of UHMWPE to a large degree. It is also obvious that studies on the wear properties of PCU have been significantly less compared to UHMWPE and further focussed studies will make it clearer for the question of an alternative to UHMWPE for lumbar disc material.

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Declarations

Conflict of interest The authors declare no competing interest.

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