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Review Article

Advances in tribological testing of artificial joint biomaterials using multidirectional pin-on-disk testers

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ABSTRACT

The introduction of numerous formulations of Ultra-high molecular weight polyethylene (UHMWPE), which is widely used as a bearing material in orthopedic implants, necessitated screening of bearing couples to identify promising iterations for expensive joint simulations. Pin-on-disk (POD) testers capable of multidirectional sliding can correctly rank formulations of UHMWPE with respect to their predictive *in vivo* wear behavior. However, there are still uncertainties regarding POD test parameters for facilitating clinically relevant wear mechanisms of UHMWPE. Studies on the development of POD testing were briefly summarized. We systematically reviewed wear rate data of UHMWPE generated by POD testers. To determine if POD testing was capable of correctly ranking bearings and if test parameters outlined in ASTM F732 enabled differentiation between wear behavior of various formulations, mean wear rates of non-irradiated, conventional (25–50 kGy) and highly crosslinked (≥90 kGy) UHMWPE were grouped and compared. The mean wear rates of non-irradiated, conventional and highly crosslinked UHMWPEs were 7.03, 5.39 and 0.67 mm^3/MC. Based on studies that complied with the guidelines of ASTM F732, the mean wear rates of non-irradiated, conventional and highly crosslinked UHMWPEs were 0.32, 0.21 and 0.04 mm^3/km, respectively. In both sets of results, the mean wear rate of highly crosslinked UHMPWE was smaller than both conventional and non-irradiated UHMWPEs ($p<0.05$). Thus, POD testers can compare highly crosslinked and conventional UHMWPEs despite different test parameters. Narrowing the allowable range for standardized test parameters could improve sensitivity of multi-axial testers in correctly ranking materials.

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Contents

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) has been used as a bearing material in orthopedic implants since 1962 (Kurtz, 2009). In 2006, more than 500 000 primary total joint replacement operations were performed in the US alone (Kurtz, 2009). The number of these operations is expected to increase in the future and the majority of patients receiving total hip replacements are projected to be less than 65 years of age (Kurtz, 2009). The wear resistance of UHMWPE is sufficient that even for younger patients the total hip components would not wear through in the lifetime of a patient based on wear rates of retrieved acetabular cups (Kurtz et al., 1999; Turell et al., 2005, 2003). However, generation of billions of sub-micron wear particles during the service of implants was implicated in causing cellular responses leading to implant loosening and osteolysis in both hip and knee replacements (Kurtz et al., 1999; McKellop et al., 1978; Oral et al., 2004; Saikko and Ahlroos, 1999; Turell et al., 2003; Wang, 2001). Various strategies have been employed by researchers to improve the wear resistance of UHMWPE in an attempt to increase implant longevity (Kurtz et al., 1999). Modifying processing steps (Barbour et al., 1999; Gul et al., 2003), crosslinking followed by heat treatments and antioxidant additives (Muratoglu et al., 1999; Muratoglu et al., 2003; Oral et al., 2010; Oral et al., 2004), composites (Deng and Shalaby, 1997), alternative counterbearings (Dowson and Harding, 1982; McKellop et al., 1978; Miller et al., 1974; Saikko and Ahlroos, 1999; Shen and Dumbleton, 1974), and even coatings of UHMWPE and the counterface (Hill et al., 2008; Pavoor et al., 2006) were evaluated. The introduction of all these designs and different materials brought about the need to practically and economically screen various bearing couples to identify only the most promising iterations for expensive joint simulations (Dumbleton et al., 1974; Dumbleton, 1978; Wright et al., 1982).

The first wear tester was built in 1960 for Sir. John Charnley, who was one of the inventors of contemporary total joint arthroplasty (Kurtz, 2009). Since then, various wear tester designs and testing conditions were considered that reflected the current understanding of UHMWPE and the wear mechanisms associated with its *in vivo* use. Earlier wear testers relied on Archard's law that wear rate of UHMWPE depended on load and sliding distance only (Archard, 1953). Unidirectional disk-on-plate (Galante and Rostoker, 1973), unidirectional pin-on-disk (Barbour et al., 1999; Brown et al., 1976; Cooper et al., 1993; Dowson and Harding, 1982; Klapperich et al., 1999; Seedhom et al., 1973; Tetreault and Kennedy, 1989), bi-directional thrust-washer (Miller et al., 1974), reciprocating pin-on-disk or pin-on-plate (Cooper et al., 1993; Deng and Shalaby, 1997; McKellop et al., 1978; Wang et al., 1997) and unidirectional sphere-on-disk (Rose et al., 1982) were early designs in accordance with the theory.

Wear rates obtained with unidirectional and reciprocating motion were two to three orders of magnitude smaller compared to *in vivo* wear rates of UHMWPE (Saikko and Ahlroos, 1999; Wang et al., 1997). From very early on it transpired that multidirectional motion was a large accelerator of UHMWPE wear, and that necessitated multidirectional pin-on-disk testing to capture physiologically realistic levels of wear in artificial joints with UHMWPE bearings (Charnley, 1976; Walker et al., 1996; Wright et al., 1982).

Bragdon et al. (1996) demonstrated the importance of multidirectional motion on the wear rate of UHMWPE on a hip simulator. Wang (2001) and Wang et al. (1998, 1997, 1996, 1995).published a comprehensive series of studies comparing a linear reciprocating pin-on-disk tester with a hip joint simulator thus solidly established the importance of cross shear on the wear rate of UHMWPE and attempted to model and quantify the effects of cross shear on the wear rate. Even under reciprocal but repetitive unidirectional sliding motion, UHMWPE crystalline lamellae have been shown microscopically to realign along the direction of interfacial sliding motion. This acted like strain-hardening against such repetitive motion. The corollary to this is a drop in the wear resistance when motion occurred in the transverse direction to the predominant (or previous direction). Material failure due to wear occurred at substantially lower stress levels with increasing angle of cross-shear (sometimes described as motion with “cross paths”).

In 1999, clinically relevant magnitudes of wear were finally attainable beginning with the circularly translating pin-on-disk tester (Saikko, 1998) and multidirectional pin-on-disk testers that acknowledged the dependence of wear rate on cross-shear (Bragdon et al., 2001; Mazzucco and Spector, 2003, 2004; Muratoglu et al., 1999; Muratoglu et al., 2003; Oral et al., 2004; Saikko and Kostamo, 2011; Sathasivam et al., 2001; Turell et al., 2005; Turell et al., 2003).

Although joint simulators were available as early as 1976 (Dumbleton, 1978), they were not included in this review (see Kurtz, 2009) for a thorough review of knee simulators and their history). Our focus here was on material wear testers that were simple, yet capable and affordable enough for screening a large number of materials before more elaborate joint simulator tests were warranted.

In spite of advancements in the fundamental understanding of polyethylene wear, there are still uncertainties regarding pin-on-disk test parameters for facilitating clinically relevant wear mechanisms of UHMWPE (Mazzucco and Spector, 2003, 2004). It was also suggested that absolute test parameters for closely simulating *in vivo* conditions might not be available for these simplified testers (Dumbleton, 1978; McKellop et al., 1978). However, standardization of parameters would at least enable direct comparison between results from across and within laboratories (Dumbleton, 1978; Rostoker and Galante, 1979). ASTM F732 (ASTM, 2011) provides a general guideline for selecting test parameters with which wear rates that are predictive of *in vivo* service can be generated. The aim of this study was to address the following questions in the light of recent studies: (1) What was the historical context for the development of multi-directional pin-on-disk testing? (2) Is pin-on-disk testing capable of correctly ranking bearings with respect to their predictive *in vivo* wear resistance? (3) Are the test parameters outlined in ASTM F732 sufficient to reveal the potential differences in wear behavior of various formulations of UHMWPE?

2. Search strategy and criteria

Studies were retrieved from Google Scholar and PubMed databases, Wear and Biomaterials journals, which were queried using “UHMWPE” AND “PIN-ON-DISK”. These studies were used in summarizing the development of pin-on-disk section. Studies where multi-axial pin-on-disk testers were employed were selected from above for analysis in the results section.

3. Development of pin-on-disk testing

Since the 1970s, the procedure for the development of orthopedic bearings initiated with screening of several candidate materials by simple and affordable testing machines. The promising candidates would then be tested in a joint simulator followed by *in vivo* testing of the most promising material (Dumbleton et al., 1974). There are important differences between pin-on-disk material testing and full artificial joint (*e.g.* knee) simulator testing. The latter tests the overall combination of implant design as well as the bearing materials, and therefore is inevitably more complex and costly (Haider and Garvin, 2008; Haider and Kaddick, 2012; Haider et al., 2012; Kurtz, 2009). This makes it more necessary to have the pin-on-disk testing done right with meaningful and conclusive results, hopefully predictive of their *in vivo* wear resistance. Therefore, identifying the set of parameters that would enable screening of materials on a simplified apparatus such as a pin-on-disk testers has been the focus of numerous studies (McKellop et al., 1978). Early studies attempted to compare wear rates obtained in the laboratories with clinical wear rates (Dumbleton, 1978) of 0.13 mm/year for Charnley prostheses in an attempt to validate testing conditions (Dumbleton et al., 1974). While the effects of lubricants were studied using dry, water and serum lubrication (Dowson and Harding, 1982; Dumbleton and Shen, 1976; McKellop et al., 1978; Tetreault and Kennedy, 1989), there was no consensus regarding the wear measurement technique (Brown et al., 1976; Dowson and Harding, 1982; Seedhom et al., 1973). Measurements were either based on changes in polyethylene weight or height. Although the volumetric measurements camp advocated their method on the grounds that attached wear debris and fluid uptake did not affect the specimen height (Charnley, 1976; Seedhom et al., 1973; Shen and Dumbleton, 1974), gravimetric measurements were not affected by creep and plastic deformation (McKellop et al., 1978). Studies comparing both techniques reported that volumetric measurements yielded higher scatter (Dowson and Harding, 1982; McKellop et al., 1978). The difficulty of obtaining a linear wear rate based on height changes due to creep (Rostoker and Galante, 1979) helped establish gravimetric measurements as the standard wear measurement technique in pin-on-disk testing. Caution is necessary with wear estimates which rely on thickness (or surface scanning) measurements due to potential creep and shape recovery errors associated with viscoelastic deformation and some shape memory properties of UHMWPE (Lee and Pienkowski, 1998).

It was acknowledged at this time that obtaining a wear rate similar to clinical values did not guarantee that similar wear mechanisms were active due to the simplifications introduced by the setup (Dumbleton, 1978; McKellop et al., 1978). Consequently, researchers began examining articulating surfaces and comparing them to those from retrieved implants in order to evaluate whether the wear mechanisms were similar (Brown et al., 1976; McKellop et al., 1978). Surface evaluations revealed that dry lubrication resulted in melting of the surface, which caused delamination and polyethylene transfer (Dowson and Harding, 1982; Dumbleton and Shen, 1976; Tetreault and Kennedy, 1989) and led to the high wear rates when the product of pressure and velocity limit of the material was exceeded (Dumbleton and Shen, 1976; Rose et al., 1982; Shen and Dumbleton, 1974). While water lubrication also displayed polyethylene transfer (Cooper et al., 1993; McKellop et al., 1978; Tetreault and Kennedy, 1989), which was not clinically relevant, serum lubrication produced scratches on otherwise burnished surfaces similar to those of retrieved implants (McKellop et al., 1978; Rose et al., 1982; Walker et al., 1996; Wright et al., 1982). Thus, it was established that serum or other protein containing lubrication was required in laboratory tests to facilitate wear mechanisms similar to those *in vivo* (Ahlroos, 2001; McKellop et al., 1978; Rose et al., 1982; Saikko, 2003; Walker et al., 1996; Wright et al., 1982; Yao et al., 2003).

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Even after serum lubrication and gravimetric quantification of wear were established, wear factors on simplified testers such as unidirectional pin-on-disk and reciprocating pin-on-flat testers (~10^{-8} mm^3/N m, Saikko, 1998) were one to three orders of magnitude smaller than *in vivo* wear factors in total hip arthroplasty (THA) (~10^{-6} mm^3/N m, Saikko, 1998) and in total knee arthroplasty (TKA) due to simplified geometry and testing conditions (Bragdon et al., 2001; Dumbleton, 1978; Saikko and Ahlroos, 1999; Turell et al., 2005; Wang et al., 1997). The goal of studies employing pin-on-disk testing was to obtain ranking of materials that is free from uncontrolled implant design effects based on their relative wear rates rather than absolute wear rates (Dumbleton, 1978; McKellop et al., 1978; Wright et al., 1982). For instance, McKellop et al. (1981) showed on a reciprocating pin-on-disk tester that both polytetrafluoroethylene (PTFE) and polyester displayed significantly higher wear rates than UHMWPE, which was in agreement with clinical findings. Rose et al. (1982) produced decreasing wear rates when molecular weight or irradiation dose of UHMWPE was increased on a unidirectional ball-on-flat tester, which were also clinically relevant findings. However, Wang et al. (1997) compared ethylene oxide (EtO) sterilized UHMWPE with crosslinked UHMWPE, which was gamma irradiated with a dose of 25 kGy and stabilized in nitrogen, on both a linear reciprocating tester and a multi-axial hip joint simulator to test whether the ranking of relative wear rates would remain unchanged between the two testing machines. Crosslinked UHMWPE produced a higher wear rate than EtO sterilized UHMWPE on the linear reciprocating pin-on-plate tester whereas EtO sterilized UHMWPE produced three times as much wear than crosslinked UHWMPE on the multi-axial hip joint simulator. The authors concluded that a clinically relevant rank of materials was not ensured only with *in vivo* contact stresses independent of loading and motion configurations; multidirectional sliding contact was required for facilitating wear mechanisms relevant to those *in vivo* (Wang et al., 1997). Saikko (1998)built a multidirectional pin-on-disk tester where the sliding direction with respect to the pin rotated. On this device, 25 kGy gamma irradiated UHMWPE specimens were tested against stainless steel disks and a wear factor of 0.8×10^{-6} mm^3/N m, which was comparable to clinical values, was obtained (Saikko, 1998). Bragdon et al. (2001)Bragdon et al. compared a multidirectional motion hip simulator with a bi-directional pin-on-disk tester and produced similar wear rates (10 mg/MC compared to 35 mg/MC). Muratoglu et al. (1999) tested UHMWPE with various radiation doses ranging from 25 to 300 kGy on a bi-directional pin-on-disk tester and showed that the wear factor decreased with increasing crosslinking density. On another study, Saikko et al. (2001) compared GUR 1020 that was gamma irradiated by 25 kGy in nitrogen with GUR 1050 that was electron beam irradiated by 95 kGy and remelted on a multidirectional pin-on-disk tester. They produced an average wear factor of 2×10^{-6} mm^3/Nm for conventional UHMWPE, which is close to clinical values, and 2×10^{-9} mm^3/Nm for highly crosslinked UHMWPE (Saikko et al., 2001). These findings, which were clinically relevant, established the importance of multidirectional motion in eliciting wear behavior similar to *in vivo*. The importance of multidirectional motion to *in vivo* wear mechanisms was also evidenced by quasi-elliptical tracks observed in implants from hip (Bragdon et al., 1996; Bragdon et al., 2001) and knee joints (Korduba and Wang, 2011). The opposite effects of crosslinking on unidirectional and multidirectional wear helped researchers in discovering the relationship between wear mechanisms of UHMWPE and the molecular reorientation of its chains (Saikko and Ahlroos, 1999; Turell et al., 2003; Wang et al., 1997). Linear sliding contact resulted in orientation of chains in the direction of sliding, which led to strain hardening. After reorientation, it was harder to rupture fibers in the sliding direction by breaking C–C bonds, but the fibers were now more vulnerable to be separated from each other in the perpendicular direction by breaking van der Wals molecular bonds. This mechanism was believed to be similar to *in vivo* wear mechanisms of UHMWPE and it explained why multidirectional wear was necessary to produce clinically relevant wear rates (Saikko and Ahlroos, 1999; Turell et al., 2003; Wang et al., 1997). The molecular reorientation of UHMWPE was also verified by SEM (Bragdon et al., 1996; Gul et al., 2003; Korduba and Wang, 2011) and TEM analyses (Klapperich et al., 1999). Crosslinking, on the other hand, retarded orientation-softening and resulted in higher wear resistance in multidirectional wear (Klapperich et al., 1999; Muratoglu et al., 1999; Wang et al., 1997). With the inclusion of multidirectional sliding, pin-on-disk testers were now capable of correctly ranking different formulations of UHMWPE with respect to their wear behavior as obtained by joint simulators (Greenbaum et al., 2004).

3.1. *Test parameters*

Now that clinically relevant wear mechanisms could be facilitated on multidirectional pin-on-disk testers, test parameters that would produce clinically relevant rankings of materials based on their wear rates had to be identified. Before proceeding with the summary of relevant test parameters, it should be noted that since 1970s, wear behavior of polyethylene has been reported as a wear factor (Seedhom et al., 1973). According to Archard's law (1953), volume of wear debris generated is proportional to load and sliding distance by a wear factor (Brown et al., 1976; Dumbleton et al., 1974; Seedhom et al., 1973), which is assumed to be constant independent of magnitude of load (McKellop et al., 1978). An alternative parameter for reporting wear behavior is volumetric/gravimetric wear per sliding distance/number of cycles (Matsubara and Watanabe, 1967; Mazzucco and Spector, 2003; McKellop et al., 1978), which does not require assumptions about the wear behavior. Wear factor, in theory, permits comparison of wear rates obtained with any loads and any sliding distances per cycle whereas wear volume per million cycles requires that same testing conditions such as contact area and contact pressure if results from different studies were to be compared. Historically, wear rates were also converted to depth of wear (mm/year) (Rostoker and Galante, 1976; Shen and Dumbleton, 1974) by dividing volumetric wear by (nominal) contact area to permit comparisons with clinical radiographs (Dumbleton et al., 1974).

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3.2. Multidirectional motion

Studies showed that the wear factor was determined by cross-shear and emphasized the importance of the aspect ratio of wear tracks on the wear behavior (Korduba and Wang, 2011; Saikko et al., 2004; Turell et al., 2003; Wang, 2001). Turell et al. (2003) suggested that differences in gait patterns of patients could produce disparate *in vivo* wear rates even when other factors such as age and body proportions were similar (Turell et al., 2003). The modeling of wear for UHMWPE, which was based on total friction work and only considered the work in the secondary sliding direction regarding generation of wear debris, confirmed the effect of cross shear on the wear rate of conventional UHMWPE (Wang, 2001). The unified model anticipated the highest wear rate using a square shaped wear track. Saikko et al. (2004) showed that wear factor decreased as aspect ratio increased in the range of 1–5.5 above which the wear factor became smaller than $10^{-6}\,\text{mm}^3/\text{N m}$, which confirmed the unified model. However, in another study, it was shown that wear factor increased with increasing aspect ratios in the range of 1–2.33 while the total sliding distance was kept constant. The critical aspect ratio was found to be 2.33 above which the wear factor became smaller (Turell et al., 2003). Korduba and Wang (2011) also found the critical aspect ratio to be 4, which resulted in highest wear factor, for conventional UHMWPE and reported that highly crosslinked UHMWPE with a total irradiation dose of 90 kGy was unaffected by changing aspect ratios. Finally, in another study, wear of moderately irradiated (with a dose of 40 and 50 kGy) UHMWPE was found to be higher right after discrete cross shear events and dropped to almost zero in ~5 mm of unidirectional sliding (Dressler et al., 2011). This finding challenged the validity of using wear factors and Archard's law, which anticipated that wear was proportional to sliding distance. Alternative modeling efforts have since emerged to try to predict the effects of cross shear on UHMWPE wear. Literally all of those were empirical in nature, and most were motivated by the need to model wear at least a bit more realistically in computational simulation methods such as by explicit FEA solvers. Among them was an attempt to characterize and numerically quantify the cross shear aspects of articular paths (Hamilton et al., 2005). Another modeled the “strain hardening and creep” (Willing and Kim, 2009). Others went further to literally introduce new wear laws or the foundations for such laws for whole artificial implants (Abdelgaied et al., 2011; Kang et al., 2009; Strickland et al., 2011). A recent study, on the other hand, tried to incrementally improve upon the earlier models of wear (by Wang's group) with “orientation softening” (Lee et al., 2011). An interesting recent study (Petrella et al., 2012) introduced a novel cross-shear model which took into consideration in their computations not only the cross-path changes for each discretized articular surface element but also the historical (time) from when those path changes occurred, the most recent being most additive to wear. All those efforts are yet to be more thoroughly vetted, and confirmed by solid experimental evidence. Therefore, they will in turn most likely spurn a new generation of pin-on-disk testing results beyond the ones reviewed below.

3.3. Contact area and stress

Numerous studies have focused on the effects of axial load and contact area on the wear behavior of UHMWPE (Mazzucco and Spector, 2003, 2004; Rostoker and Galante, 1979; Saikko, 2006). Although the wear factor assumed a linear relationship between wear volume and load, studies showed that the same magnitude of load can generate different wear rates if contact area was changed (Mazzucco and Spector, 2003, 2004; Sathasivam et al., 2001). Mazzucco and Spector (2003) reported three regimes of wear behavior depending on contact stress. Below a contact stress threshold, wear was minimal. Within physiologically relevant contact stresses up to 7 MPa, wear rate increased with increasing contact area, which suggested that wear increased when more asperities came into contact, and load did not correlate with wear rate. Finally, above a certain contact stress threshold, delamination wear started and increasing contact stress resulted in higher wear rates (Mazzucco and Spector, 2003). Sathasivam et al. confirmed this pattern by varying the contact area while applying the same load. Under this constant magnitude of axial load, wear was almost zero up to 5.3 MPa in stress. Decreasing the contact area further resulted in a higher contact stress regime where an inverse relationship between contact stress and wear rate was observed, similar to findings of Mazzucco and Spector (2003). Even though the magnitude of axial load was kept constant, larger contact areas produced higher wear rates (Sathasivam et al., 2001). These studies suggested that wear factor should be proportional to contact area instead of axial load within physiologically relevant contact stresses. In another study, the converse was tested; the contact area was kept constant while the axial load was varied to evaluate its effect on wear rate (Saikko, 2006). Wear rate was shown to increase as load increased up to a critical range of contact stresses between 2 and 3.5 MPa. Beyond this limit, wear factor and wear rate decreased as load increased and articulating surfaces stopped displaying clinically relevant surface features (Saikko, 2006). The magnitudes of critical contact stresses reported in these studies were not comparable possibly because different loads and contact areas were employed. Nevertheless, these studies indicated the presence of regimes of varying wear behavior, which should be taken into account when comparing results from different studies. Finally, in a recent study, dynamic loading was compared to static loading on a multi-axial pin-on-disk tester and it was concluded that the wear rate did not depend on the loading scheme (Saikko and Kostamo, 2011) despite earlier postulations that static loading could result in high wear rates due to lubricant starvation (Charnley, 1976; Dumbleton, 1978; Walker et al., 1996). These results suggested that Archard's law might not be able to successfully model wear characteristics of UHMWPE bearings.

3.4. Counterface roughness

The detrimental effects of third body wear due to acrylic bone cement particles or bone particles, which scratched the counterface and enabled abrasive wear between the counterface and polymer, were known to researchers early on Cooper

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et al. (1993), McKellop et al. (1978) and Saikko et al. (2001). Researchers suggested that wear testing using polished counterfaces represented only the ideal wear scheme for *in vivo* conditions and additional tests had to be performed on promising materials to ensure that the polymer would not immediately fail under abrasive wear and the rank-order of relative wear rates of polymers would not change against rougher surfaces (Barbour et al., 1999; McKellop et al., 1978, 1981). Saikko et al. (2001) showed that wear factor increased with counterface roughness and wear factor of highly cross-linked and heat treated UHMWPE against rough counterface was still smaller than that of conventional UHMWPE against smooth counterface.

In the next section, we analyzed and compared results from the literature, where multi-axial pin-on-disk testers were employed, and results from our laboratory, which were generated on an OrthoPOD pin-on-disk tester (AMTI, Watertown, USA) and a 100 station circularly translating pin-on-disk tester (Super-CTPOD) (Phoenix Tribology, Newbury, England). We evaluated whether ranks of relative wear rates obtained from pin-on-disk testers agree with clinical findings even though *in vitro* testing represents an ideal wear regime with controlled variables, smooth counterfaces and no bone cement or bone particles within the contact (McKellop et al., 1978). We also evaluated whether the parameters provided by ASTM F732 produced testing conditions that could expose potential differences in wear resistance of various formulations of UHMWPE.

4. Systematic review of pin-on-disk testing results

For the wear rate analysis of UHMWPE on pin-on-disk testers, 23 studies where multidirectional motion was employed were selected from 52 studies reviewed. Analysis was limited to 19 studies where the average roughness of counterface material was smaller than 0.2 μm and cylindrical pins with flat articulating surfaces were used. UHMWPE specimens tested in these studies were manufactured from different resins (GUR 4150, 1020 and 1050), but they were grouped together for analysis with respect to the radiation dose they received. The mean wear factor of non-irradiated UHMWPE was 1.93×10^{-6} mm^3/N m based on 11 studies (Fig. 1). Conventional PE with a radiation dose between 25 and 50 kGy yielded a mean wear factor of 1.03×10^{-6} mm^3/N m based on seven studies, (Fig. 1). Finally, the mean wear factor analysis for highly crosslinked (irradiation dose of 90 kGy or higher) UHMWPE resulted in 0.13×10^{-6} mm^3/N m based on six studies (Fig. 1). Wear factor of highly crosslinked UHMWPE was smaller than the wear factors of conventional and non-irradiated UHMWPEs ($p=0.03$; $p<0.001$; Kruskal–Wallis test). Differences between wear factors of conventional UHMWPE and non-irradiated UHMWPEs were not statistically significant ($p=0.11$). It should be noted that the use of wear factors could be misleading since it assumes that wear depends primarily on load, and implies that a higher contact area under the same load would necessarily produce lesser wear. Mazzucco and Spector, 2003, 2004 showed that wear rate correlated with contact area instead of load for a range of contact stresses. This was confirmed unequivocally in full knee simulator tests (Haider et al., 2012), where the wear of larger total knee replacement systems was significantly more than smaller implants, under the same loading and with two types of UHMWPE, conventional and Vitamin-E stabilized highly crosslinked. *In vitro* and *in vivo* hip replacement wear results confirm this generally, too.

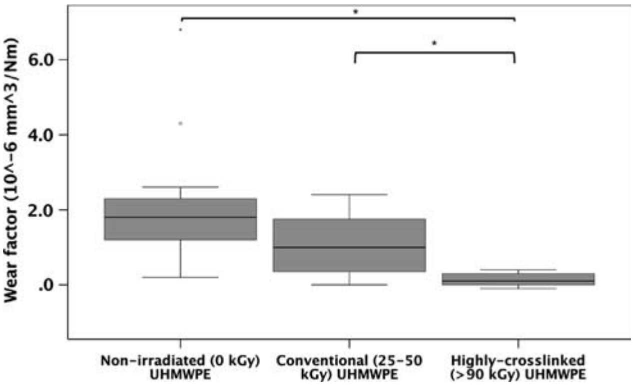

Fig. 1 – The wear factors of non-irradiated, conventional and highly crosslinked UHMWPE obtained from pin-on-disk tests.

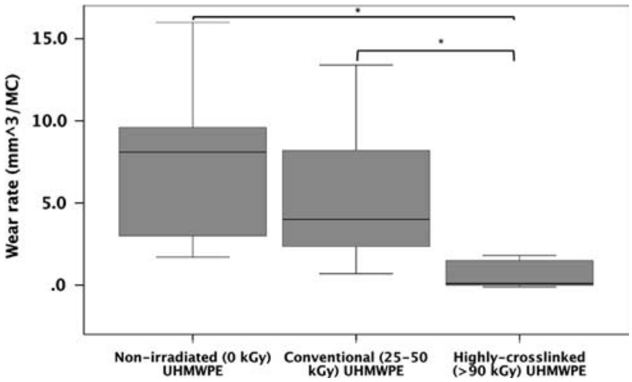

Fig. 2 – The wear rates of non-irradiated, conventional and highly crosslinked UHMWPE obtained from pin-on-disk tests.

Volumetric wear rates from these studies were also analyzed in order to compare the wear behavior of formulations of UHMWPE. The mean wear rate of non-irradiated UHMWPE was 7.03 mm^3/MC based on 11 studies (Fig. 2). The mean wear rate of conventional UHMWPE, on the other hand, was 5.39 mm^3/MC based on seven studies (Fig. 2), which can be compared to 7 mm^3/MC, the (perhaps too simplistically quoted) clinically relevant average wear rate of gamma irradiated UHMWPE in THAs according to ASTM F732. Finally, the mean wear rate of highly crosslinked UHMWPE was 0.67 mm^3/MC based on six studies (Fig. 2). The wear rate of highly crosslinked UHMPWE was smaller than both conventional and non-irradiated UHMWPEs ($p=0.001$; $p<0.001$; Kruskal–Wallis test). The difference between conventional and non-irradiated UHMWPEs was not statistically significant ($p=1$; Kruskal–Wallis test). It should be noted that sliding distance per

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Table 1 – Test parameters and results of studies where multidirectional pin-on-disk tester were used to characterize wear behavior of UHMWPE. Studies, which were suitable for analysis in this review, were indicated with "1" in the suitability column.

Study	Pin material	Irradiation	Irradiation grouped	Molecular weight	Disk material	Average wear Rate (mg/MC)	Average Wear rate (mm^3/MC)	Average wear factor ($10^6 mm^3$/N m)	Load (N)	Contact Area (mm^2)
Saikko (1998)	25 kGy GUR 4150	25	2	50	Stainless Steel	1.7	1.8	0.8	70.7	7.07–63.62 (conical pin)
Muratoglu et al. (1999)	25 kGy GUR 4150	25	2	50	CoCr	9.1	9.7	0.4	max 1557 (dynamic)	
Muratoglu et al. (1999)	40 kGy GUR 4150	40	2	50	CoCr	6.3	6.7	0.3	max 1557 (dynamic)	
Saikko and Ahlroos (1999)	25 kGy GUR 4150	25	2	50	Stainless Steel	17.9	19.0	8.6	70.7	7.07–63.62 (conical pin)
Saikko and Ahlroos (1999)	25 kGy GUR 4150	25	2	50	Alumina	10.0	10.6	4.8	70.7	7.07–63.62 (conical pin)
Bragdon et al. (2001)	GUR 4150	0	1	50	CoCr	10.4	11.1	1.3	Max 310.8 (dynamic)	63.62
Bragdon et al. (2001)	GUR 4150	0	1	50	CoCr	10.0	10.6	1.2	Max 310.8 (dynamic)	63.62
Saikko et al. (2001)	25–40 kGy in nitrogen, GUR 1020	25–40	2	20	CoCr	4.1	4.4	2.0	70.7	62.49
Saikko et al. (2001)	95 kGy and remelted GUR 1050	95	3	50	CoCr	0.0	0.0	0.0	70.7	62.49
Saikko et al. (2001)	25–40 kGy in nitrogen, GUR 1020	25–40	2	20	CoCr	20.6	22.2	10.0	70.7	62.49
Saikko et al. (2001)	95 kGy and remelted GUR 1050	95	3	50	CoCr	2.0	2.2	1.0	70.7	62.49
Sathasivam et al. (2001)	4150 HP	0	1	50	CoCr	0.1	0.1		1200	415.5
Sathasivam et al. (2001)	4150 HP	0	1	50	CoCr	1.6	1.7		1200	113
Gul et al. (2003)	GUR 4050; hydrostatic pressure at 250 °C	0	1	50	CoCr	8.8	9.3	2.3	Max 267 (dynamic)	63.57
Gul et al. (2003)	GUR 4150; ram extrusion	0	1	50	CoCr	9.9	10.5	2.6	Max 267 (dynamic)	63.57
Mazzucco and Spector (2003)	GUR 1150	0	1	50	CoCr	6.5	7.0	0.8	223	31.7
Mazzucco and Spector (2003)	GUR 1150	0	1	50	CoCr	15.0	16.0	1.8	223	71.3
Muratoglu et al. (2003)	38 kGy in air, GUR 1050	38	2	50	CoCr	12.5	13.4	2.4	Max 381.7 (dynamic)	63.62
Muratoglu et al. (2003)	38 kGy in nitrogen, GUR 1050	38	2	50	CoCr	10.3	11.0	1.9	Max 381.7 (dynamic)	63.62

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Table 1 (*continued*)

Study	Pin material	Irradiation	Irradiation grouped	Molecular weight	Disk material	Average wear Rate (mg/MC)	Average Wear rate (mm^3/MC)	Average wear factor ($10^6 mm^3$/N m)	Load (N)	Contact Area (mm^2)
Muratoglu et al. (2003)	100–110 gamma, annealed, GUR 1050	100–110	3	50	CoCr	1.6	1.7	0.3	Max 381.7 (dynamic)	63.62
Muratoglu et al. (2003)	50 kGy, remelted, GUR 1050	50	2	50	CoCr	5.3	5.7	1.0	Max 381.7 (dynamic)	63.62
Muratoglu et al. (2003)	e-beam irradiated 100 kGy, remelted, GUR 1050	100	3	50	CoCr	1.0	1.1	0.2	Max 381.7 (dynamic)	63.62
Saikko (2003)	25–40 kGy gamma irradiated in nitrogen, GUR 1020	25–40	2	20	CoCr	2.2	2.4	1.1	70.7	62.49
Saikko (2003)	25–40 kGy gamma irradiated in nitrogen, GUR 1020	25–40	2	20	CoCr	2.0	2.2	1.0	70.7	62.49
Turell et al. (2003)	GUR 1050	0	1	50	CoCr	7.9	8.3	2.2	192	63.62
Turell et al. (2003)	GUR 1050	0	1	50	CoCr	8.0	8.4	2.2	192	63.62
Turell et al. (2003)	GUR 1050	0	1	50	CoCr	9.2	9.7	2.5	192	63.62
Turell et al. (2003)	GUR 1050	0	1	50	CoCr	2.9	3.1	0.8	192	63.62
Turell et al. (2003)	GUR 1050	0	1	50	CoCr	1.7	1.8	0.5	192	63.62
Yao et al. (2003)	GUR 1050	0	1	50	CoCr	5.6	6.0	0.2	445	63.62
Yao et al. (2003)	37 kGy gamma irradiated in air GUR 4150	37	2	50	CoCr	2.5	2.6	0.1	445	63.62
Yao et al. (2003)	37 kGy gamma irradiated in nitrogen GUR 1050	37	2	50	CoCr	0.7	0.7	0.0	445	63.62
Yao et al. (2003)	100 kGy electron beamed, melt annealed GUR 1050	100	3	50	CoCr	0.1	0.1	0.0	445	63.62
Greenbaum et al. (2004)	GUR 1050	0	1	50	CoCr	9.8	10.4	1.8	Max 381.7 (dynamic)	63.62
Greenbaum et al. (2004)	95 kGy and remelted GUR 1050	95	3	50	CoCr	1.4	1.5	0.3	Max 381.7 (dynamic)	63.62
Oral et al. (2004)	65 kGY, vitamin-E doping, 27 kGY GUR 1050	92	3	50	CoCr	1.5	1.6	0.3	Max 381.7 (dynamic)	63.62
Oral et al. (2004)	100 kGY, vitamin-E doping, 27 kGY GUR 1050	100	3	50	CoCr	0.9	0.9	0.2	Max 381.7 (dynamic)	63.62
Saikko (2005)	25–40 kGy gamma irradiated in nitrogen, GUR 1020	25–40	2	20	CoCr	3.4	3.6	1.6	70.7	63.62
Turell et al. (2005)	GUR 1050	0	1	50	CoCr	11.0	11.6	3.0	192	63.62
Turell et al. (2005)	GUR 1050	0	1	50	CoCr	8.4	8.9	2.3	192	63.62

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Turell et al. (2005)	GUR 1050	0	1	50	CoCr	8.1	8.5	2.2	192	63.62
Turell et al. (2005)	GUR 1050	0	1	50	CoCr	8.3	8.8	2.3	192	63.62
Turell et al. (2005)	GUR 1050	0	1	50	CoCr	14.0	14.9	3.9	192	63.62
Turell et al. (2005)	GUR 1050	0	1	50	CoCr	8.9	9.5	2.5	192	63.62
Turell et al. (2005)	GUR 1050	0	1	50	CoCr	9.6	10.2	2.6	192	63.62
Turell et al. (2005)	GUR 1050	0	1	50	CoCr	3.3	3.5	0.9	192	63.62
Turell et al. (2005)	GUR 1050	0	1	50	CoCr	6.4	6.8	1.8	192	63.62
Turell et al. (2005)	GUR 1050	0	1	50	CoCr	2.7	2.9	0.8	192	63.62
Hill et al. (2008)	25–40 kGy irradiated in Argon	25–40	2	50	CoCr	2.2	2.3	0.6	102	17.8
Oral et al. (2010)	150 kGY irradiated, vit-e blended compression molded GUR 1050	150	3	50	CoCr	1.7	1.8	0.4	Max 310.8 (dynamic)	63.62
Dressler et al. (2011)	40 kGy in vacuum pouch GUR 1020	40	2	20	CoCr	4.5	4.8	2.9	330	71.2
Dressler et al. (2011)	50 kGy irradiated and remelted GUR 1020	50	2	20	CoCr	2.3	2.5	1.5	330	71.2
Dressler et al. (2011)	40 kGy in vacuum pouch GUR 1020	40	2	20	CoCr	4.8	5.2	1.6	330	71.2
Dressler et al. (2011)	50 kGy irradiated and remelted GUR 1020	50	2	20	CoCr	2.3	2.5	0.7	330	71.2
Korduba and Wang (2011)	GUR 1020	0	1	20	CoCr	1.7	1.8	1.2	75	71.2
Korduba and Wang (2011)	GUR 1020	0	1	20	CoCr	1.6	1.7	1.2	75	71.2
Korduba and Wang (2011)	GUR 1020	0	1	20	CoCr	2.4	2.6	1.7	75	71.2
Korduba and Wang (2011)	GUR 1020	0	1	20	CoCr	2.6	2.8	1.9	75	71.2
Korduba and Wang (2011)	GUR 1020	0	1	20	CoCr	2.1	2.2	1.5	75	71.2
Korduba and Wang (2011)	(30 kGY and annealing) x3 GUR 1020	90	3	20	CoCr	0.0	0.0	0.0	75	71.2
Korduba and Wang (2011)	(30 kGY and annealing) x3 GUR 1020	90	3	20	CoCr	−0.1	−0.1	−0.1	75	71.2

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Table 1 (*continued*)

Study	Pin material	Irradiation	Irradiation grouped	Molecular weight	Disk material	Average wear Rate (mg/MC)	Average Wear rate (mm^3/MC)	Average wear factor ($10^6 mm^3$/N m)	Load (N)	Contact Area (mm^2)
Korduba and Wang (2011)	(30 kGY and annealing) ×3 GUR 1020	90	3	20	CoCr	0.1	0.1	0.1	75	71.2
Korduba and Wang (2011)	(30 kGY and annealing) ×3 GUR 1020	90	3	20	CoCr	0.0	0.0	0.0	75	71.2
Korduba and Wang (2011)	(30 kGY and annealing) ×3 GUR 1020	90	3	20	CoCr	0.0	0.0	0.0	75	71.2
Saikko and Kostamo (2011)	GUR 1020	0	1	20	CoCr	9.0	9.7	4.3	71	63.62
Saikko and Kostamo (2011)	GUR 1020	0	1	20	CoCr	7.1	7.6	6.8	71 random (0–142)	63.62
Exponent POD	GUR 1020	0	1	20	CoCr	7.5	8.1	1.8	77.5	71.2
Exponent SuperPOD	GUR 1020	0	1	20	CoCr	7.4	8.1	2.5	128	63.62
Exponent SuperPOD	vitamin-e blended GUR 1020	0	1	20	CoCr	6.0	6.5	2.0	128	63.62

Contact Stress (MPa)	Aspect Ratio (A/B)	Sliding Velocity (mm/s)	Sliding distance (mm)	Average Counterface Roughness (micrometers)	Lubricant	Tester	Comments	Normalized wear rate (mm^3/km)	Suitability	Reason for exclusion
10.0–3.0 (conical pin)	1 (circle)	32	31.42	0.004–0.005	Adult bovine serum	Custom (CTPOD)		0.057	0	conical pins
	2 (square)		30	0.01±0.001	Bovine serum	Custom (Bi-axial POD)	tables read g/MC should read mg/MC; density assumed 0.94 mg/mm3; peroxide crosslinked specimens were not included	0.323	1	
	2 (square)		30	0.01±0.001	Bovine serum	Custom (Bi-axial POD)		0.223	1	
10.0–3.0 (conical pin)	1 (circle)	32	31.42	0.003	Adult bovine serum	Custom (CTPOD)	Authors suggested machining surfaces exposed effects of oxidation leading to higher wear; only serum lubricated samples	0.606	0	conical pins
10.0–3.0 (conical pin)	1 (circle)	32	31.42	0.006	Adult bovine serum	Custom (CTPOD)		0.339	0	conical pins

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Max 4.8 (dynamic)	2 (square)	30	30	0.05±0.006	Bovine serum	Custom (Bi-axial POD)	density assumed 0.94 mg/mm3	0.369	1	
Max 4.8 (dynamic)	2 (square)	60	30	0.05±0.006	Bovine serum	Custom (Bi-axial POD)	density assumed 0.94 mg/mm3	0.355	1	
1.1	1 (circle)	32	31.42	0.014–0.027	Alpha Calf Fraction serum (21 g/L)	Custom (CTPOD)	density was given as 0.93 mg/mm3	0.140	1	
1.1	1 (circle)	32	31.42	0.014–0.027	Alpha Calf Fraction serum (21 g/L)	Custom (CTPOD)	density was given as 0.93 mg/mm4	0.000	1	
1.1	1 (circle)	32	31.42	0.2	Alpha Calf Fraction Serum (21 g/L)	Custom (CTPOD)	density was given as 0.93 mg/mm5	0.707	0	high roughness
1.1	1 (circle)	32	31.42	0.2	Alpha Calf Fraction Serum (21 g/L)	Custom (CTPOD)	density was given as 0.93 mg/mm6	0.070	0	high roughness
2.8	10 mm reciprocating +5% rotation	10	10	0.01–0.03	calf serum	Custom (reciprocating and rotating)	two stress values were picked	0.012	0	high roughness
10.6	10 mm reciprocating +5% rotation	10	10	0.01–0.03	calf serum	Custom (reciprocating and rotating)		0.168	0	high roughness
Max 4.2 (dynamic)	2 (square)	60	30	0.01±0.001	Bovine serum	Custom (Bi-axial POD)	density assumed 0.94 mg/mm3; one processing temperature was selected and presented here	0.310	1	
Max 4.2 (dynamic)	2 (square)	60	30	0.01±0.001	Bovine serum	Custom (Bi-axial POD)	density assumed 0.94 mg/mm3	0.350	1	
7	1 (square)	40	40	0.025–0.05	Bovine calf serum	OrthoPOD	lubrication protocol B was reported here	0.175	1	
3.1	1 (square)	40	40	0.025–0.05	Bovine calf serum	OrthoPOD	lubrication protocol B was reported here	0.400	1	
Max 6 (dynamic)	2 (square)	60	30	0.05±0.006	Bovine serum	Custom (Bi-axial POD)	density assumed 0.93 mg/mm3	0.447	1	
Max 6 (dynamic)	2 (square)	60	30	0.05±0.006	Bovine serum	Custom (Bi-axial POD)	density assumed 0.93 mg/mm3	0.367	1	
Max 6 (dynamic)	2 (square)	60	30	0.05±0.006	Bovine serum	Custom (Bi-axial POD)	density assumed 0.93 mg/mm3	0.057	1	
Max 6 (dynamic)	2 (square)	60	30	0.05±0.006	Bovine serum	Custom (Bi-axial POD)	density assumed 0.93 mg/mm3	0.190	1	

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Table 1 (*continued*)

Contact Stress (MPa)	Aspect Ratio (A/B)	Sliding Velocity (mm/s)	Sliding distance (mm)	Average Counterface Roughness (micrometers)	Lubricant	Tester	Comments	Normalized wear rate (mm^3/km)	Suitability	Reason for exclusion
Max 6 (dynamic)	2 (square)	60	30	0.05±0.006	Bovine serum	Custom (Bi-axial POD)	density assumed 0.93 mg/mm3	0.037	1	
1.1	1 (circle)	32	31.42	0.012±0.003	Alpha Calf serum (20 g/L)	Custom (CTPOD)	only 20 ang 30 g/L results are used	0.076	1	
1.1	1 (circle)	32	31.42	0.012±0.003	Alpha Calf serum (30 g/L)	Custom (CTPOD)	density was given as 0.93 mg/mm3	0.070	1	
3	1 (square)	20	20	0.015	Bovine serum (23 g/L)	OrthoPOD	density was given as 0.943 mg/mm3	0.417	1	
3	1.5 (square)	20	20	0.015	Bovine serum (23 g/L)	OrthoPOD	density was given as 0.943 mg/mm3	0.422	1	
3	2.3 (square)	20	20	0.015	Bovine serum (23 g/L)	OrthoPOD	density was given as 0.943 mg/mm3	0.486	1	
3	4 (square)	20	20	0.015	Bovine serum (23 g/L)	OrthoPOD	density was given as 0.943 mg/mm3	0.154	1	
3	9 (square)	20	20	0.015	Bovine serum (23 g/L)	OrthoPOD	density was given as 0.943 mg/mm3	0.090	1	
7	1 (square)	60	60	0.003±0.001	Bovine serum (0.69 g/L)	Custom	density assumed 0.94 mg/mm3	0.100	1	
7	1 (square)	60	60	0.003±0.001	Bovine serum (0.69 g/L)	Custom	density assumed 0.94 mg/mm3	0.044	1	
7	1 (square)	60	60	0.003±0.001	Bovine serum (0.69 g/L)	Custom	density assumed 0.94 mg/mm^3	0.012	1	
7	1 (square)	60	60	0.003±0.001	Bovine serum (0.69 g/L)	Custom	density assumed 0.94 mg/mm^3	0.001	1	
Max 6 (dynamic)	2 (square)	60	30		Bovine serum	Custom (Bi-axial POD)	density assumed 0.94 mg/mm^3	0.348	1	
Max 6 (dynamic)	2 (square)	60	30		Bovine serum	Custom (Bi-axial POD)	density assumed 0.94 mg/mm^3	0.050	1	

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Max 6 (dynamic)	2 (square)	60	30	0.05±0.006	Bovine serum	Custom (Bi-axial POD)	density assumed 0.94 mg/mm^3	0.052	1	
Max 6 (dynamic)	2 (square)	60	30	0.05±0.006	Bovine serum	Custom (Bi-axial POD)	density assumed 0.94 mg/mm^3	0.031	1	
1.1	1 (circle)	31.4	31.4	0.01–0.02	Bovine serum (21 g/L)	Super-CTPOD	density was given as 0.94 mg/mm^3	0.115	1	
3	1 (square)	20	20	0.45	Bovine serum (23 g/L)	OrthoPOD	density was given as 0.943 mg/mm^3	0.582	0	high roughness
3	1 (square)	20	20	0.015	Bovine serum (23 g/L)	OrthoPOD	density was given as 0.943 mg/mm^3	0.445	1	
3	1.5 (square)	20	20	0.45	Bovine serum (23 g/L)	OrthoPOD	density was given as 0.943 mg/mm^3	0.427	0	high roughness
3	1.5 (square)	20	20	0.015	Bovine serum (23 g/L)	OrthoPOD	density was given as 0.943 mg/mm^3	0.441	1	
3	2.3 (square)	20	20	0.45	Bovine serum (23 g/L)	OrthoPOD	density was given as 0.943 mg/mm^3	0.745	0	high roughness
3	2.3 (square)	20	20	0.015	Bovine serum (23 g/L)	OrthoPOD	density was given as 0.943 mg/mm^3	0.473	1	
3	4 (square)	20	20	0.45	Bovine serum (23 g/L)	OrthoPOD	density was given as 0.943 mg/mm^3	0.508	0	high roughness
3	4 (square)	20	20	0.015	Bovine serum (23 g/L)	OrthoPOD	density was given as 0.943 mg/mm^3	0.173	1	
3	9 (square)	20	20	0.45	Bovine serum (23 g/L)	OrthoPOD	density was given as 0.943 mg/mm^3	0.339	0	high roughness
3	9 (square)	20	20	0.015	Bovine serum (23 g/L)	OrthoPOD	density was given as 0.943 mg/mm^3	0.145	1	
5.71	1 (square)	60	40		Bovine serum (23 g/L)	OrthoPOD	density was given as 0.933 mg/mm^3	0.058	1	
Max 4.8 (dynamic)	2 (square)	60	30	0.02	Bovine serum	Custom (Bi-axial POD)	density assumed 0.94 mg/mm^3	0.060	1	
4.7	reciprocate rotation	64	5	<0.01	Bovine serum	OrthoPOD	density was assumed as 0.93 mg/mm^3	0.968	0	not multi-axial
4.7	reciprocate +rotation	64	5	<0.01	Bovine serum	OrthoPOD	density was assumed as 0.93 mg/mm^3	0.495	0	not multi-axial
4.7	reciprocate +rotation	64	10	<0.01	Bovine serum	OrthoPOD	density was assumed as 0.93 mg/mm^3	0.516	0	not multi-axial
4.7	reciprocate +rotation	64	10	<0.01	Bovine serum	OrthoPOD	density was assumed as 0.93 mg/mm^3	0.247	0	not multi-axial

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Table 1 (*continued*)

Contact Stress (MPa)	Aspect Ratio (A/B)	Sliding Velocity (mm/s)	Sliding distance (mm)	Average Counterface Roughness (micrometers)	Lubricant	Tester	Comments	Normalized wear rate (mm^3/km)	Suitability	Reason for exclusion
1.05	1 (square)	20	20	<0.01	Bovine serum (20 g/L)	OrthoPOD	density was assumed as 0.93 mg/mm^3	0.089	1	
1.05	1.5 (square)	20	20	<0.01	Bovine serum (20 g/L)	OrthoPOD	density was assumed as 0.93 mg/mm^3	0.087	1	
1.05	2.3 (square)	20	20	<0.01	Bovine serum (20 g/L)	OrthoPOD	density was assumed as 0.93 mg/mm^3	0.130	1	
1.05	4 (square)	20	20	<0.01	Bovine serum (20 g/L)	OrthoPOD	density was assumed as 0.93 mg/mm^3	0.141	1	
1.05	9 (square)	20	20	<0.01	Bovine serum (20 g/L)	OrthoPOD	density was assumed as 0.93 mg/mm^3	0.112	1	
1.05	1 (square)	20	20	<0.01	Bovine serum (20 g/L)	OrthoPOD	density was assumed as 0.93 mg/mm^3	−0.002	1	
1.05	1.5 (square)	20	20	<0.01	Bovine serum (20 g/L)	OrthoPOD	density was assumed as 0.93 mg/mm^3	−0.005	1	
1.05	2.3 (square)	20	20	<0.01	Bovine serum (20 g/L)	OrthoPOD	density was assumed as 0.93 mg/mm^3	0.006	1	
1.05	4 (square)	20	20	<0.01	Bovine serum (20 g/L)	OrthoPOD	density was assumed as 0.93 mg/mm^3	0.002	1	
1.05	9 (square)	20	20	<0.01	Bovine serum (20 g/L)	OrthoPOD	density was assumed as 0.93 mg/mm^3	0.002	1	
1.1	1 (circle)	31.4	31.4	0.01	Bovine serum	RandomPOD	density was given as 0.93 mg/mm^3	0.308	1	
1.1 random (0–2.2)	random multidirectional	15.7 (random)	15.7	0.01	Bovine serum	RandomPOD	random slidetrack wear factor was based on the average	0.486	1	
1.1	2 (circle)	59.2	59.2	<0.005	Bovine serum (20 g/L)	OrthoPOD	density was 0.935 mg/mm^3	0.136	1	
2	2 (circle)	24.8	24.8	<0.005	Bovine serum (20 g/L)	Super-CTPOD	density was given as 0.924 mg/mm^3	0.325	1	
2	2 (circle)	24.8	24.8	<0.005	Bovine serum (20 g/L)	Super-CTPOD	density was given as 0.92 mg/mm^3	0.262	1	

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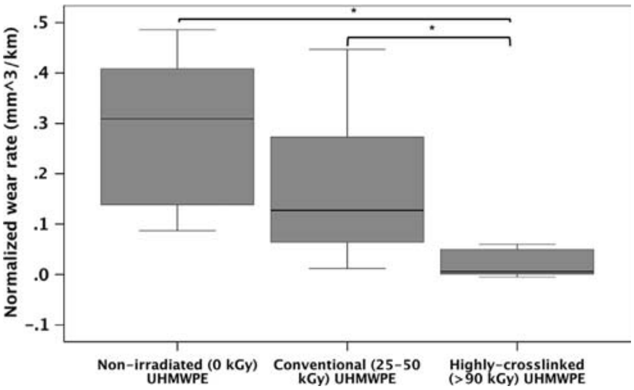

Fig. 3 – The normalized wear rates of non-irradiated, conventional and highly crosslinked UHMWPE obtained from pin-on-disk tests. Wear rates were normalized to total sliding distance per million cycles in each study.

cycle in these studies varied between 15 and 60 mm (Table 1). Although calculation of the wear factor takes into account the differences in sliding distances between tests, direct comparison based on wear rates might be invalidated when sliding distances are different between studies.

Since wear had been expected by some to nominally increase with sliding distance per cycle (Archard, 1953; McKellop et al., 1978), the wear rates from each study were normalized to the corresponding total sliding distance per million cycles to attempt more direct comparisons. For non-irradiated UHMWPE, the mean normalized wear rate was 0.28 mm^3/km based on 11 studies (Fig. 3). The mean wear rate of conventional UHMWPE, on the other hand, was 0.17 mm^3/km based on seven studies (Fig. 3). The mean wear rate analysis of highly crosslinked UHMWPE resulted in 0.02 mm^3/km based on six studies (Fig. 3). Similar to the mean wear rates per million cycles (mm^3/MC), the mean wear rates normalized to total sliding distance (mm^3/km) showed that highly crosslinked UHMWPE was more wear resistant than both conventional and non-irradiated UHMWPEs ($p=0.008$; $p<0.001$; Kruskal–Wallis test). The difference between the wear rates of conventional and non-irradiated UHMWPEs was not statistically significant when the wear rates were normalized ($p=0.21$; Kruskal–Wallis test).

Finally, 7 studies of the 19 studies analyzed above were found not to comply with the guidelines of ASTM F732 because either the sliding distance per cycle was smaller than 25 mm or maximum contact stress was smaller than 2 MPa. Based on the remaining 12 studies, mean normalized wear rates of non-irradiated, conventional and highly crosslinked UHMWPEs were 0.32, 0.21 and 0.04 mm^3/km respectively. Similar to previous findings, the mean normalized wear rate of highly crosslinked UHMWPE was found to be lower than both conventional and non-irradiated UHMWPEs, and the difference between conventional and non-irradiated UHMWPEs was not statistically different ($p=0.03$; $p<0.001$; $p=0.12$; Tukey post-hoc analysis with one-way ANOVA).

5. Discussion

The primary aim of this study was to provide an overview of the major developments in screening of formulations of UHMWPE as bearing material for orthopedic implants using pin-on-disk testers. The most important development in this field was the incorporation of multidirectional motion (Bragdon et al., 2001; Saikko and Ahlroos, 1999; Wang, 2001), which enabled simplified pin-on-disk testers to correctly rank materials with respect to their wear resistance as determined by joint simulators (Greenbaum et al., 2004).

The second aim of this study was to review published results characterizing wear behavior of UHMWPE using pin-on-disk testers to evaluate whether results generated in laboratories agreed with clinical findings. For this purpose, wear rates of numerous formulations of UHMWPE were grouped with respect to the irradiation dose they received for sterilization and/or crosslinking. Based on studies conducted with different test parameters, this review of results in the literature showed that the wear resistance of highly crosslinked UHMWPE was higher than that of conventional UHMWPE, which was in turn higher than that of non-irradiated UHMWPE. Despite varying test conditions (Table 1), the range of results for these formulations indicated that highly crosslinked UHMWPE could be differentiated from conventional and non-irradiated UHMWPEs based on wear factors and wear rates. Since wear increases linearly with sliding distance, the effect of testing at different sliding distances per cycle between studies could impair direct comparisons based on wear rates. Wear rates in these studies were then normalized to the total sliding distance per million cycles in each study to enable their direct comparison. However, it was still not possible to statistically differentiate between non-irradiated and conventional UHMWPE based on normalized wear rates. Before multidirectional testers were available, it was suggested that simplified testers were only capable of comparing materials with seemingly different properties (Wang et al., 1997). It was shown that results generated by pin-on-disk testers could be used to compare highly crosslinked UHMWPE and conventional UHMWPE even if test parameters varied.

The third aim of this study was to evaluate whether formulations of UHMWPE could be compared based on pin-on-disk tests where testing conditions were different but within the boundaries of ASTM F732 specifications. This analysis indicated whether differences in wear behavior of polyethylene that was exposed to different doses of radiation could be masked by the variability caused by changing testing conditions within a range allowed by the ASTM standard. For this aim, studies where the peak contact stress did not exceed 2 MPa and the sliding distance per cycle was shorter than 25 mm, were further eliminated. It was found that, once again, the difference in normalized wear rates of conventional and non-irradiated UHMWPEs was not statistically significant. This finding has two implications. First, it is imperative that candidate materials be tested simultaneously along with control specimens serving as baseline. Second, comparing test results with ones from the published

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literature might not be conclusive even if test parameters in studies of interest comply with ASTM F732. Based on load, contact area and stress, the active wear mechanism could differ between studies (Mazzucco and Spector, 2003, 2004; Saikko, 2006; Sathasivam et al., 2001) and comparisons can be undermined.

This review has limitations. In order to cover a wider range of studies, formulations of UHMWPE manufactured by different processes and having different molecular weights were grouped together. The rationale was that the effects of irradiation crosslinking would be more profound than the uncertainty caused by differences in manufacturing and/or molecular weight. Also, there was variation in reported protein concentration of bovine serum used in a number of studies, which were nevertheless grouped together. Although protein concentration is known to affect wear rates, this effect was expected to be smaller than that of crosslinking since most studies used bovine serum with protein concentrations of either 20 or 30 g/L. In addition, the range of aspect ratios indicative of amount of cross-shear, in these studies, varied from 1 to 9, but mean wear rates and wear factors were calculated in this review depending on formulation but not with respect to amount of cross-shear. Finally, only mean wear rates and mean wear factors were retrieved from studies analyzed for this review; standard deviations were omitted.

In an attempt to investigate whether employing testers of different designs contributed to the variation in wear rates of UHMWPE, two studies (one of them was conducted in our laboratory) where Super-CTPOD was used were compared (Saikko, 2005). Although the tested material was 25–40 kGy GUR 1020 in one study (Saikko, 2005), non-irradiated GUR 1020 was tested in the other study. The wear rates were 3.6 and 8.1 mm^3/MC while contact stresses were 1.1 and 2 MPa. The variation in wear rates could be attributed to changes in testing parameters. When three studies (Korduba and Wang, 2011; Mazzucco and Spector, 2003; Turell et al., 2003) and another study conducted in our laboratory employing OrthoPOD were compared, on the other hand, mean wear rates of non-irradiated UHMWPE varied between 1.74 and 16.0 mm^3/MC while contact stress only varied between 1 and 7 MPa. The difference in wear rates was attributed to varying magnitudes of cross-shear. Finally, two studies performed in our laboratory were compared where OrthoPOD and Super-CTPOD were employed (Table 1). The mean wear rates of GUR 1020 were 8.05 and 8.06 mm^3/MC, respectively. Although test parameters were different (Table 1), similar amounts of wear were generated. These observations showed that different testers operating with comparable test parameters could generate much similar results compared to identical testers operating with different test parameters. In addition, it was observed that an increased number of test parameters have to be specified for more advanced testers in order to generate comparable results.

These findings emphasized the importance of standardized test parameters in order to minimize the variation between test results. Although multi-axial testers can correctly rank materials with respect to wear behavior, minimizing the allowable range for test parameters would ensure a higher reproducibility of results even when testers of different designs were employed.

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REFERENCES

Abdelgaied, A., Liu, F., Brockett, C., Jennings, L., Fisher, J., Jin, Z., 2011. Computational wear prediction of artificial knee joints based on a new wear law and formulation. Journal of Biomechanics 44, 1108–1116.

Ahlroos, T., 2001. Effect of lubricant on the wear of prosthetic joint materials. Acta Polytechnica Scandinavica, Me, 153.

Archard, J., 1953. Contact and rubbing of flat surfaces. Journal of Applied Physics 24, 981–988.

ASTM, 2011. F 732-00. Standard Test Method for Wear Testing of Polymeric Materials Used in Total Joint Prostheses. Annual Book of ASTM Standards, 212–217.

Barbour, P., Stone, M., Fisher, J., 1999. A study of the wear resistance of three types of clinically applied UHMWPE for total replacement hip prostheses. Biomaterials 20, 2101–2106.

Bragdon, C., O'Connor, D., Lowenstein, J., Jasty, M., Syniuta, W., 1996. The importance of multidirectional motion on the wear of polyethylene. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 210, 157–165.

Bragdon, C.R., O'Connor, D.O., Lowenstein, J.D., Jasty, M., Biggs, S. A., Harris, W.H., 2001. A new pin-on-disk wear testing method for simulating wear of polyethylene on cobalt-chrome alloy in total hip arthroplasty. The Journal of Arthroplasty 16, 658–665.

Brown, K., Atkinson, J., Dowson, D., Wright, V., 1976. The wear of ultrahigh molecular weight polyethylene and a preliminary study of its relation to the *in vivo* behaviour of replacement hip joints. Wear 40, 255–264.

Charnley, J., 1976. The wear of plastics materials in the hip joint. Plastics and Rubber 1, 59–63.

Cooper, J., Dowson, D., Fisher, J., 1993. The effect of transfer film and surface roughness on the wear of lubricated ultra-high molecular weight polyethylene. Clinical Materials 14, 295–302.

Deng, M., Shalaby, S.W., 1997. Properties of self-reinforced ultra-high-molecular-weight polyethylene composites. Biomaterials 18, 645–655.

Dowson, D., Harding, R., 1982. The wear characteristics of ultrahigh molecular weight polyethylene against a high density alumina ceramic under wet (distilled water) and dry conditions. Wear 75, 313–331.

Dressler, M.R., Strickland, M.A., Taylor, M., Render, T.D., Ernsberger, C.N., 2011. Predicting wear of UHMWPE: Decreasing wear rate following a change in direction. Wear.

Dumbleton, J., Shen, C., 1976. The wear behavior of ultrahigh molecular weight polyethylene. Wear 37, 279–289.

Dumbleton, J., Shen, C., Miller, E., 1974. A study of the wear of some materials in connection with total hip replacement. Wear 29, 163–171.

Dumbleton, J.H., 1978. Wear and its measurement for joint prosthesis materials. Wear 49, 297–326.

Galante, J.O., Rostoker, W., 1973. Wear in total hip prostheses. An experimental evaluation of candidate materials. Acta Orthopaedica Scandinavica. Supplementum 145, 1.

Greenbaum, E.S., Burroughs, B.B., Harris, W.H., Muratoglu, O.K., 2004. Effect of lipid absorption on wear and compressive

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properties of unirradiated and highly crosslinked UHMWPE: An *in vitro* experimental model. Biomaterials 25, 4479–4484.

Gul, R.M., McGarry, F.J., Bragdon, C.R., Muratoglu, O.K., Harris, W. H., 2003. Effect of consolidation on adhesive and abrasive wear of ultra high molecular weight polyethylene. Biomaterials 24, 3193–3199.

Haider, H., Garvin, K., 2008. Rotating platform *versus* fixed-bearing total knees: an *in vitro* study of wear. Clinical Orthopaedics and Related Research 466, 2677–2685.

Haider, H., Kaddick, C., 2012. Wear of mobile bearing knees: is it necessarily less?. Journal of ASTM International, 9.

Haider, H., Weisenburger, J., Kurtz, S., Rimnac, C., Freedman, J., Schroeder, D., Garvin, K., 2012. Does vitamin e-stabilized ultrahigh-molecular-weight polyethylene address concerns of cross-linked polyethylene in total knee arthroplasty?. The Journal of Arthroplasty 27, 461–469.

Hamilton, M., Sucec, M., Fregly, B., Banks, S., Sawyer, W., 2005. Quantifying multidirectional sliding motions in total knee replacements. Journal of Tribology 127, 280.

Hill, M.R., Catledge, S.A., Konovalov, V., Clem, W.C., Chowdhury, S.A., Etheridge, B.S., Stanishevsky, A., Lemons, J.E., Vohra, Y. K., Eberhardt, A.W., 2008. Preliminary tribological evaluation of nanostructured diamond coatings against ultra-high molecular weight polyethylene. Journal of Biomedical Materials Research Part B: Applied Biomaterials 85, 140–148.

Kang, L., Galvin, A.L., Fisher, J., Jin, Z., 2009. Enhanced computational prediction of polyethylene wear in hip joints by incorporating cross-shear and contact pressure in additional to load and sliding distance: effect of head diameter. Journal of Biomechanics 42, 912–918.

Klapperich, C., Komvopoulos, K., Pruitt, L., 1999. Tribological properties and microstructure evolution of ultra-high molecular weight polyethylene. Journal of Tribology 121, 394–402.

Korduba, L., Wang, A., 2011. The effect of cross-shear on the wear of virgin and highly-crosslinked polyethylene. Wear 271, 1220–1223.

Kurtz, S.M., 2009. UHMWPE Biomaterials Handbook: Ultra High Molecular Weight Polyethylene in Total Joint Replacement and Medical Devices, 2nd ed. Academic Press, Burlington, MA.

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, 1659–1688.

Lee, K.Y., Pienkowski, D., 1998. Viscoelastic Recovery of Creep-Deformed Ultra-High Molecular Weight Polyethylene (UHMWPE). ASTM Special Technical Publication 1307, 30–36.

Lee, R., Korduba, L., Wang, A., 2011. An improved theoretical model of orientation softening and cross-shear wear of ultra high molecular weight polyethylene. Wear 271, 2230–2233.

Matsubara, K., Watanabe, M., 1967. The wear properties of high-density polyethylene irradiated by gamma rays. Wear 10, 214–222.

Mazzucco, D., Spector, M., 2003. Effects of contact area and stress on the volumetric wear of ultrahigh molecular weight polyethylene. Wear 254, 514–522.

Mazzucco, D., Spector, M., 2004. Contact Area as a Critical Determinant in the Tribology of Metal-on-Polyethylene Total Joint Arthroplasty. ASME.

McKellop, H., Clarke, I., Markolf, K., Amstutz, H., 1978. Wear characteristics of UHMW polyethylene: a method for accurately measuring extremely low wear rates. Journal of biomedical materials research 12, 895–927.

McKellop, H., Clarke, I., Markolf, K., Amstutz, H., 1981. Friction and wear properties of polymer, metal, and ceramic prosthetic joint materials evaluated on a multichannel screening device. Journal of Biomedical Materials Research 15, 619.

Miller, D., Ainsworth, R., Dumbleton, J., Page, D., Miller, E., 1974. A comparative evaluation of the wear of ultra-high molecular weight polyethylene abraded by Ti-6Al-4 V. Wear 28, 207–216.

Muratoglu, O.K., Bragdon, C.R., O'Connor, D.O., Jasty, M., Harris, W.H., Gul, R., McGarry, F., 1999. Unified wear model for highly crosslinked ultra-high molecular weight polyethylenes (UHMWPE). Biomaterials 20, 1463–1470.

Muratoglu, O.K., Merrill, E.W., Bragdon, C.R., O'Connor, D., Hoeffel, D., Burroughs, B., Jasty, M., Harris, W.H., 2003. Effect of radiation, heat, and aging on *in vitro* wear resistance of polyethylene. Clinical Orthopaedics and Related Research 417, 253.

Oral, E., Ghali, B.W., Rowell, S.L., Micheli, B.R., Lozynsky, A.J., Muratoglu, O.K., 2010. A surface crosslinked UHMWPE stabilized by vitamin E with low wear and high fatigue strength. Biomaterials 31, 7051–7060.

Oral, E., Wannomae, K.K., Hawkins, N., Harris, W.H., Muratoglu, O.K., 2004. α-Tocopherol-doped irradiated UHMWPE for high fatigue resistance and low wear. Biomaterials 25, 5515–5522.

Pavoor, P.V., Gearing, B.P., Muratoglu, O., Cohen, R.E., Bellare, A., 2006. Wear reduction of orthopaedic bearing surfaces using polyelectrolyte multilayer nanocoatings. Biomaterials 27, 1527–1533.

Petrella, A.J., Armstrong, J.R., Laz, P.J., Rullkoetter, P.J., 2012. A novel cross-shear metric for application in computer simulation of ultra-high molecular weight polyethylene wear. Computer Methods in Biomechanics and Biomedical Engineering 15, 1223–1232.

Rose, R., Cimino, W., Ellis, E., Crugnola, A., 1982. Exploratory investigations on the structure dependence of the wear resistance of polyethylene. Wear 77, 89–104.

Rostoker, W., Galante, J., 1976. Some new studies of the wear behavior of ultrahigh molecular weight polyethylene. Journal of Biomedical Materials Research 10, 303–310.

Rostoker, W., Galante, J., 1979. Contact pressure dependence of wear rates of ultra high molecular weight polyethylene. Journal of Biomedical Materials Research 13, 957–964.

Saikko, V., 1998. A multidirectional motion pin-on-disk wear test method for prosthetic joint materials. Journal of Biomedical Materials Research 41, 58–64.

Saikko, V., 2003. Effect of lubricant protein concentration on the wear of ultra-high molecular weight polyethylene sliding against a CoCr counterface. Journal of Tribology 125, 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, 309–318.

Saikko, V., 2006. Effect of contact pressure on wear and friction of ultra-high molecular weight polyethylene in multidirectional sliding. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 220, 723–731.

Saikko, V., Ahlroos, T., 1999. Type of motion and lubricant in wear simulation of polyethylene acetabular cup. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 213, 301–310.

Saikko, V., Calonius, O., Keränen, J., 2001. Effect of counterface roughness on the wear of conventional and crosslinked ultrahigh molecular weight polyethylene studied with a multi-directional motion pin-on-disk device. Journal of Biomedical Materials Research 57, 506–512.

Saikko, V., Calonius, O., Keränen, J., 2004. Effect of slide track shape on the wear of ultra-high molecular weight polyethylene in a pin-on-disk wear simulation of total hip prosthesis. Journal of Biomedical Materials Research Part B: Applied Biomaterials 69, 141–148.

Saikko, V., Kostamo, J., 2011. RandomPOD–A new method and device for advanced wear simulation of orthopaedic biomaterials. Journal of Biomechanics 44, 810–814.

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Sathasivam, S., Walker, P.S., Campbell, P.A., Rayner, K., 2001. The effect of contact area on wear in relation to fixed bearing and mobile bearing knee replacements. Journal of Biomedical Materials Research 58, 282–290.

Seedhom, B., Dowson, D., Wright, V., 1973. Wear of solid phase formed high density polyethylene in relation to the life of artificial hips and knees. Wear 24, 35–51.

Shen, C., Dumbleton, J., 1974. The friction and wear behavior of irradiated very high molecular weight polyethylene. Wear 30, 349–364.

Strickland, M., Dressler, M., Taylor, M., 2011. Predicting implant UHMWPE wear in-silico: a robust, adaptable computational-numerical framework for future theoretical models. Wear 274–275, 100–108.

Tetreault, D.M., Kennedy, F.E., 1989. Friction and wear behavior of ultrahigh molecular weight polyethylene on Co–Cr and titanium alloys in dry and lubricated environments. Wear 133, 295–307.

Turell, M., Friedlaender, G., Wang, A., Thornhill, T., Bellare, A., 2005. The effect of counterface roughness on the wear of UHMWPE for rectangular wear paths. Wear 259, 984–991.

Turell, M., Wang, A., Bellare, A., 2003. Quantification of the effect of cross-path motion on the wear rate of ultra-high molecular weight polyethylene. Wear 255, 1034–1039.

Walker, P.S., Blunn, G.W., Lilley, P.A., 1996. Wear testing of materials and surfaces for total knee replacement. Journal of Biomedical Materials Research 33, 159–175.

Wang, A., 2001. A unified theory of wear for ultra-high molecular weight polyethylene in multi-directional sliding. Wear 248, 38–47.

Wang, A., Essner, A., Polineni, V., Stark, C., Dumbleton, J., 1998. Lubrication and wear of ultra-high molecular weight polyethylene in total joint replacements. Tribology International 31, 17–33.

Wang, A., Polineni, V., Essner, A., Sokol, M., Sun, D., Stark, C., Dumbleton, J.H., 1997. The significance of nonlinear motion in the wear screening of orthopaedic implant materials. Journal of Testing and Evaluation 25, 239–245.

Wang, A., Stark, C., Dumbleton, J., 1996. Mechanistic and morphological origins of ultra-high molecular weight polyethylene wear debris in total joint replacement prostheses. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 210, 141–155.

Wang, A., Sun, D., Stark, C., Dumbleton, J., 1995. Wear mechanisms of UHMWPE in total joint replacements. Wear 181, 241–249.

Willing, R., Kim, I.Y., 2009. A holistic numerical model to predict strain hardening and damage of UHMWPE under multiple total knee replacement kinematics and experimental validation. Journal of Biomechanics 42, 2520–2527.

Wright, K., Dobbs, H., Scales, J., 1982. Wear studies on prosthetic materials using the pin-on-disc machine. Biomaterials 3, 41–48.

Yao, J.Q., Blanchet, T.A., Murphy, D.J., Laurent, M.P., 2003. Effect of fluid absorption on the wear resistance of UHMWPE orthopedic bearing surfaces. Wear 255, 1113–1120.

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