Wear Behaviour of CFR PEEK Articulated against CoCr under Varying Contact Stresses: Low wear of CFR PEEK negated by wear of the CoCr counterface

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Abstract

Total hip replacement with metal-on-polymer hip prostheses is the most common treatment for late-stage osteoarthritis. However, the wear debris generated from the polymer acetabular liner remains a problem. Alternative materials with claimed superior wear properties have been proposed to overcome this problem. In this study, the wear behaviour of carbon fibre reinforced polyether ether ketone (CFR PEEK) was investigated under different contact stresses that are observed in the natural hip joint. A 50-station pin-on-disc machine (SuperCTPOD) was used to investigate the wear behaviour of 50 CFR PEEK pins articulated against cobalt chromium (CoCr) discs under five different contact stresses, namely 1.11, 1.38, 1.61, 2.00 and 5.30 MPa. The results showed that the wear rates of the pins did not differ significantly between groups under different contact stresses. In addition, CFR PEEK produced lower wear rates than ultrahigh molecular weight polyethylene and cross-linked polyethylene. However, the weight of the CoCr discs was found to decrease significantly at the end of the wear test, which was indicative of metallic wear. The findings of this study indicated that, despite having relatively low wear rates, CFR PEEK is not a good alternative to be utilised against orthopaedic metals.

Keywords

Wear, in-vitro testing, carbon fibre reinforced polyether ether ketone, artificial joints

Introduction

The ball-and-socket configuration of the human hip joint enables the forces that act on the joint in various magnitudes and/or directions to be effectively supported. The average contact stresses generated from these forces ranges from 0.1 MPa to 5.6 MPa during daily life activities [1, 2]. However, these contact stresses can dramatically increase depending on the movement. For instance, a contact stress of 11 MPa has been recorded during stumbling [1, 2]. Therefore, a healthy hip joint must support the contact stresses acting on it in order to maintain its function. Due to diseases, injuries, infections and/or development conditions, the natural hip joint may need to be replaced with an artificial joint.

Osteoarthritis, the most common type of arthritis, is the main reason that necessitates joint replacement. Total hip replacement (THR) is considered to be the most successful treatment for late stage osteoarthritis [3, 4]. The most common type of artificial hip implant used for osteoarthritis treatment is the metal-on-polymer (MoP) hip [5]. Here, the femoral articulating component is usually made from cobalt chromium (CoCr) or stainless steel (SS), and the most commonly used material for the acetabular liner is cross-linked polyethylene (XLPE) [6, 7], although historically it has been ultrahigh molecular weight polyethylene (UHMWPE) [8].

There is a concern that the wear of polyethylene provokes inflammatory reactions in the body and thus implant failure. On average, a wear rate of 96 ± 13 $\frac{mm^3}{year}$ was recorded in a clinical study for the articulation of UHMWPE against CoCr and wear rates above this value were linked to osteolysis [9]. Osteolysis results in the resorption of the bone and in most cases loosening of the implant [3, 4]. Searching for alternatives to reduce the incidence of osteolysis and joint revision is a major topic in orthopaedics. This will especially be beneficial for relatively younger and more active patients suffering from osteoarthritis.

Alternative materials to UHMWPE have been proposed [10]. Polyether ether ketone (PEEK) has been introduced in orthopaedics as an alternative to UHMWPE [11], however, wear studies showed that its wear rate was up to 8 times more than that of UHMWPE [12, 13]. Historically, the wear properties of UHMWPE were tried to be improved by reinforcing it with carbon fibre. Unfortunately it was shown that the carbon fibre reinforced UHMWPE (CFR UHMWPE), also known as Poly II, was not successful because it exhibited high wear rates, fracture and excessive delamination [14] . In addition, traces of abrasive wear were observed at the metallic counter face [14].

More recently, wear rates were found to be significantly reduced when XLPE was used instead of UHMWPE [15-18]. PEEK composites, which have also been introduced as an alternative, were also found to have lower wear rates than UHMWPE [14]. Unlike UHMWPE, PEEK showed excellent compatibility with carbon fibres [14]. Studies showed that the amount of wear debris generated from carbon fibre reinforced PEEK (CFR PEEK) was lower than that of UHMWPE and the debris was found to be non-toxic [11, 14]. It was concluded that CFR PEEK may have a potential to replace the ”gold standard” orthopaedic polymer, UHMWPE [11].

While in vitro studies have provided encouraging results for the use of CFR PEEK, clinical studies are limited. The surface topography of a retrieved CFR PEEK liner that articulated against a ceramic femoral head was analysed by Pace et al. [19] and a small amount of wear (0.057 mm/year) was reported. The implant was removed after 28 months because of post-trauma infection [19]. However, the in vivo service time of the implant and the sample size were both very limited to draw conclusions about the wear performance of CFR PEEK. Field et al. [20] collected 3-year clinical and radiological data for 25 MITCH PCR acetabular cups (made of CFR PEEK). Although the short-term results were satisfactory, four of the cups had to be revised within 50 months due to squeaking and/or osteolysis [20]. There are some studies that discussed the in vivo performance of CFR PEEK for knee implants. Schierjott et al. [21] compared the in vivo and in vitro wear data of a CFR PEEK hinge mechanism of 12 rotating hinge knee implants. CFR PEEK was the material of the flanges and bushes. The retrieved implants were used in vivo for an average of 34.9 months. With no failures recorded, CFR PEEK was found to generate less wear than conventional polyethylene when articulated against a metal and a ceramic [21]. For the same type of knee implant, Böhler et al. [22] reported significantly improved knee function with an implant survival rate of 91% after five years for 50 patients. The complications observed for the retrieved implants were not linked to the CFR PEEK components [22]. These aforementioned studies gave an insight of the wear behaviour of CFR PEEK against a ceramic in the short-term, however, as a bearing material against metals, further investigation of the wear response of CFR PEEK is required.

When considering wear tests of orthopaedic biomaterials, it is imperative that wear tests are conducted under appropriate conditions and ideally that multiple test pins are tested concurrently [14, 23]. These studies are important in terms of providing data to estimate the long-term wear performance of the materials and to consider whether they could replace UHMWPE in clinical applications. Details of previous wear tests of CFR PEEK rubbing against hard counterfaces are given in table 1.

Table 1 In-vitro studies that tested the wear behaviour of CFR PEEK

Authors	**Materials tested (pin material named first)**	**Type of wear testing**	**Number of pins tested**	**Contact Stresses Tested**	**Wear Factor (x $10^{-6}\ \frac{mm^3}{Nm}$)**
Scholes and Unsworth [23]	CFR PEEK against ceramic	Pin-on-plate	4	2.00 MPa	0.18 (range: 0.13 - 0.22)
Scholes and Unsworth [24]	CFR PEEK against CoCr	Pin-on-plate	4	2.00 MPa	0.21 (range: 0.04 - 0.69)
Evans et al. [25]	CFR PEEK against ceramic	Pin-on-plate	16	0.53 - 9.75 MPa	0.79 (range: 0.01 - 3.68)
Scholes and Unsworth [24]	PEEK against CoCr	Pin-on-plate	4	2.00 MPa	7.37 (range: 4.83 – 8.60)

CFR PEEK: carbon fibre reinforced polyether ether ketone, XLPE: cross-linked polyethylene

Scholes and Unsworth [24] tested CFR PEEK against ceramic plates at a contact stress of 2 MPa and found an average wear factor of 0.18 x $10^{-6}\ \frac{mm^3}{Nm}$. Evans et al. [25] also tested the same material combination for contact stresses ranging from 0.50 to 9.98 MPa. For contact stresses below 6 MPa (the contact stresses observed in the hip joint), wear factors calculated were 10 to 100 times lower than for UHMWPE. No correlation between different contact stresses and wear factors was found for the articulation of CFR PEEK against ceramic [25]. Although articulating against ceramic, rather than metal, this is in contrast to other studies of UHMWPE and XLPE, which found that wear varied with contact stress [15, 16, 26]. Even though Evans et al. [25]'s results were encouraging for utilizing CFR PEEK in ceramic-on-polymer (CoP) hip joints, they did not reveal any information for the more commonly used MoP hips.

In another study [24], CFR PEEK was tested against CoCr and an average wear factor of 0.21 x 10^{-6} $\frac{mm^3}{Nm}$ for the pins and 0.0152 x 10^{-6} $\frac{mm^3}{Nm}$for the plates was found. In addition, PEEK articulated against CoCr was found to have a high wear rate compared to CFR PEEK articulated against the same material [24].

Recognising that MoP hips are most commonly implanted, that Poly II (CFR UHMWPE) was unsuccessful, and that there have been a slew of recent orthopaedic disasters (metal-on-metal (MoM) hips [27], modular femoral stems [28], and spinal rods [29]) where unexpected wear and material loss has occurred, we sought to investigate whether the CoCr counterface might undergo any wear when rubbed against CFR PEEK pins. We investigated the wear of CFR PEEK pins articulated against CoCr discs under different contact stresses in a high capacity wear screening machine.

The results were compared to the wear of UHMWPE and XLPE that had previously been tested using the same machine. Wear factors were used to compare the wear of CFR PEEK pin groups that had different contact stresses. Equation (1) was used to calculate the wear factors (k,$\frac{mm^3}{Nm}$).

$$k = \frac{V}{LD} \qquad \text{(Eq. 1)}$$

where V is the volume loss (mm^3), L is the load applied (N) and D is the total sliding distance (m) of the pins and discs.

Materials and Methods

A 50-station pin-on-disc machine (SuperCTPOD) (figure 1) [30] was used to investigate the wear behaviour of CFR PEEK under different contact stresses. The characteristics and working principle of the machine are described in detail elsewhere [16].

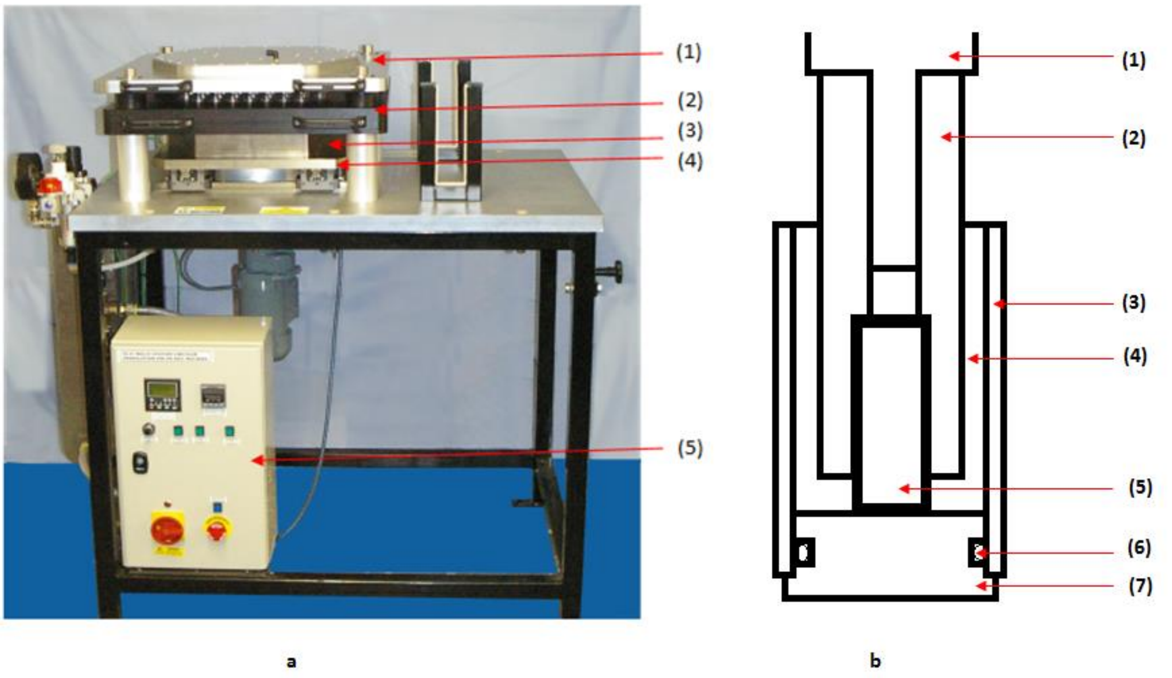

Figure 1 a) Multi-station SuperCTPOD that consists of a loading module (1), pin carrier module (2), test bath (3), motion module (4) and control unit (5), b) Schematic diagram of the pin-disc assembly showing (1) load module, (2) polyacetal pin holder, (3) PVC tube, (4) lubricant, (5) test pin, (6) silicone O-ring and (7)test disc.

CFR PEEK pins were articulated against CoCr discs, which were fitted inside PVC tubes to form the wear station assemblies. The test bath containing the 50 assemblies followed an elliptical orbital motion with a frequency of 1 Hz. A load of 70.7 N was applied to each of the test pins. The wear track path was set to 12 x 10 mm, which resulted in 34.62 mm of sliding distance per cycle. The same elliptical wear track was used previously by Harsha and Joyce [15] and Kandemir et al. [16] which made it possible to compare the wear behaviour of UHMWPE, XLPE and CFR PEEK. The test pins translated without rotation and the elliptical motion enabled the direction of motion of the discs to be changed continually with respect to the test pins, to produce wear factors similar to what is observed in vivo [30].

The 30% CFR PEEK pins were purchased in rod form from Ensinger (UK) and then machined to the desired shape and size to form the pins. The material properties provided by the supplier are summarised in table 2.

Table 2 Material properties of the CFR PEEK test pins [31].

Material Properties	Constant Value
Modulus of Elasticity	6000 MPa
Density	1.38 mg/mm^3
Tensile Strength	112 MPa
Elongation at break	10 %
Ball Indentation Hardness	298 MPa

CFR PEEK pins, which were 9 mm in outer diameter and 12 mm in height, were divided into 5 groups. The number of pins required for each group was estimated using a statistical analysis, described elsewhere [16], and 9 pins were found to be statistically sufficient. Apart from group 1 (1.1MPa), the pins from each group were drilled with different diameter holes, having an annulus height of 2 mm, see figure 2. The same annulus height was used by Vassiliou and Unsworth [26] in a study in which the influence of contact stress on the wear of UHMWPE was tested. The annulus enabled different contact areas to be formed between the CFR PEEK pins and CoCr discs, and consequently, different contact stresses to be tested. Drilling resulted in the wear surface of the pins to be as far from the centreline as possible, thus maximizing the second moment of area and reducing any potential deflection of the wearing surface. The initial surface roughness values of the pin groups prior to the experiment were measured as 0.73 ± 0.16, 1.794 ± 0.10, 1.461 ± 0.16, 2.352 ± 0.27 and 3.170 ± 0.37 µm, respectively (figure 5).

Figure 2 CFR PEEK test pins. From left to right, pin from group 1 (1.11 MPa), group 2 (1.38 MPa), group 3 (1.61 MPa), group 4 (2.00 MPa) and group 5 (5.30 MPa). Red circles were drawn for better contrast of the annulus.

Each test pin articulated against its corresponding CoCr disc, which was of 28 mm diameter, 10 mm thickness, and polished to less than 0.050 µm Ra. The inner and outer diameter values of the pins prior to the experiment and the corresponding contact areas and contact stresses are given in table 3. The contact stresses tested ranged from 1.11 to 5.30 MPa and were clinically relevant [1, 2].

Table 3 The inner and outer diameters of the pins of each group and their corresponding contact area and contact stress values.

Group number	Number of pins in the group	Outer diameter (mm)	Inner diameter (mm)	Contact area (mm^2)	Contact stress (MPa)
1	10	9.00 ± 0.02	-	63.62	1.11
2	10	9.00 ± 0.02	4.00 ± 0.23	51.05	1.38
3	10	9.00 ± 0.02	5.00 ± 0.16	43.98	1.61
4	10	9.00 ± 0.02	6.00 ± 0.12	35.34	2.00
5	10	9.00 ± 0.02	8.00 ± 0.24	13.35	5.30

The pin carrier module with the pins and the test bath holding the disc assemblies filled with lubricant are shown in figure 3.

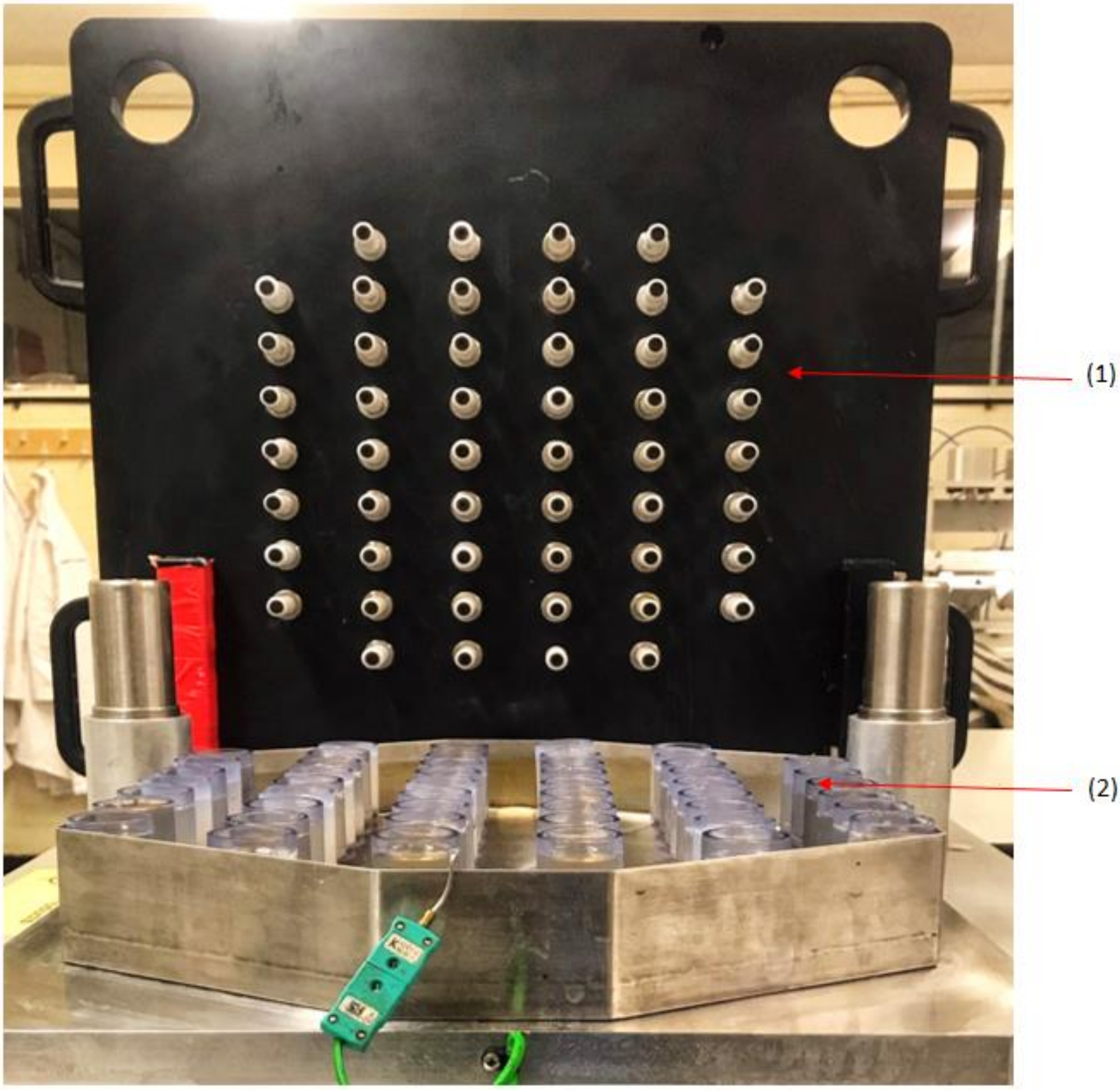

Figure 3 (1) The CFR PEEK test pins inside polyacetal sleeves located on the pin carrier module, (2) the CoCr disc assemblies, containing the lubricant, located on the test bath.

The lubricant used in the test was diluted newborn calf serum (Thermo Fisher Scientific, USA). The optimum protein concentration of the lubricant used in wear tests was suggested as 22 g/L by Saikko[32]. Hence, the lubricant used was diluted with deionized water to have a protein content of 22 g/L, and every assembly contained approximately 16 ml of lubricant.

Before starting the experiment, all the pins and discs were cleaned, weighed and numbered, and their surface roughness values (Sa) were measured. The experiment stopped every 250,000 cycles to replace the lubricant, and surface roughness and gravimetric measurements of pins and discs were taken every 500,000 cycles. The weight measurements were undertaken using a Kern ABT 220-5DM balance, which had a resolution of 10 µg. To calculate the wear factor given in equation 1 for the test pins after 2.5

million cycles, the measured weight loss values for the pin groups were converted to wear volumes using the density of the CFR PEEK which is 1.38 mg/mm^3 [31]. The surface roughness measurements of the discs and the pins were obtained using a ZYGO New View 5000 non-contacting profilometer which has a sensitivity of 0.001 µm, Sa [33]. The ASTM F732-17 "Standard Test Method for Wear Testing of Polymeric Materials Used in Total Joint Prostheses-Annex 2" provided guidance to perform the wear test.

The cleaning and drying protocol followed for the pins and discs was as follows: when the test was stopped the pins, the discs and all other equipment used in the experiment were placed in containers containing diluted disinfectant (Virkon). After 5 minutes, every component was rinsed under tap water and allowed to dry in air. The pins and disc were further washed with Isopropanol alcohol, and then allowed to dry in air for 30 minutes.

When the gravimetric and surface roughness measurements were completed, the components were renumbered and relocated at the same stations on the pin holder module before beginning a new cycle of testing. In every pin group, an additional pin was used as a control pin to track any change in weight due to lubricant uptake. The lubricant absorption measured from these control pins was taken into account in calculations of weight change and thus of wear.

Results

A summary of the results of the pin groups is given in table 4.

Table 4 Summary of the wear rates and wear factors of the pin groups

Test pin group	Wear Rate (mg/Mc) ± SD	Wear Factor (mm^3/Nm) x10^{-6} ± SD
Group 1 (1.11 MPa)	1.59 ± 1.34	0.42 ± 0.40
Group 2 (1.38 MPa)	0.65 ± 0.15	0.19 ± 0.04
Group 3 (1.68 MPa)	0.61 ± 0.38	0.18 ± 0.11
Group 4 (2.00 MPa)	0.58 ± 0.17	0.17 ± 0.05
Group 5 (5.30 MPa)	0.65 ± 0.13	0.19 ± 0.04

Mc: million cycles, SD: standard deviation

The weight gains from the control pins were found to be 0.81, 0.99, 0.88, 0.84 and 0.75 mg for pins in Groups 1 to 5, respectively, which were almost one order of magnitude higher than the weight gains measured for XLPE [16]. These values were taken into account when calculating the total weight lost from the test pins. Taking the weight gains from the control pins into consideration, the total weight lost from the pin groups were calculated to be 3.97 ± 1.23, 1.72 ± 0.23, 1.52 ± 0.24, 1.67 ± 0.34, and 1.63 ± 0.34 mg for contact stress of 1.11, 1.38, 1.61, 2.00, and 5.30 respectively (figure 4). The weight changes measured from the control discs were not found to be significant (ANOVA, p-value: 1.00) and they were not considered in the calculations. Three pins from group 1 (1.11 MPa) had higher wear rates, compared to the other 6 pins in the same group, between 1.5 to 2.0 million cycles, and one of these pins continued to have a higher wear rate (3.21 $\frac{mg}{Mc}$) until 2.5 million cycles.

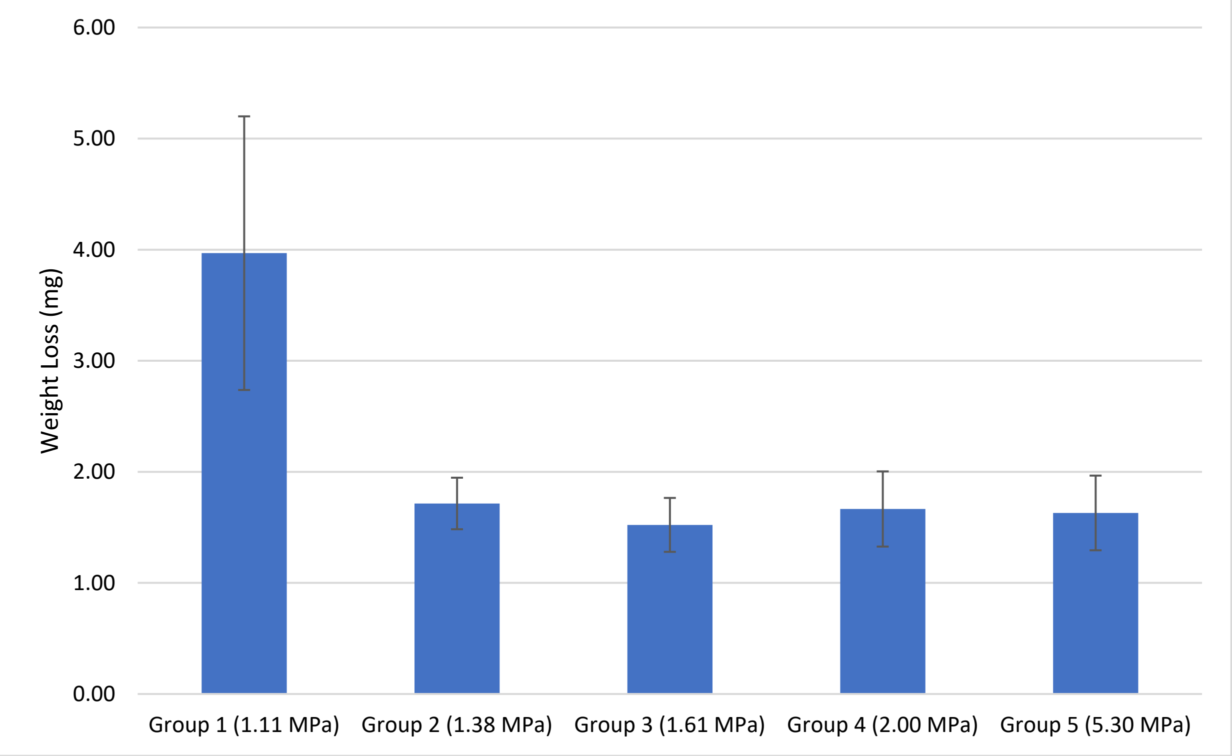

Figure 4 Total weight loss from the pin groups at the end of the experiment.

Weight loss from groups 2-5 were found to be insignificant (ANOVA, p-value: 0.797) when compared to each other, however when compared with group 1 the difference was significant (ANOVA, p-value: 0.007).

Before the experiment, the surface roughness values of the test pins were 1.55 ± 0.16, 1.55 ± 0.10, 2.00 ± 0.16, 2.15 ± 0.27 and 3.21 ± 0.37 µm, for group 1 (1.11 MPa), group 2 (1.38 MPa), group 3 (1.61 MPa), group 4 (2.00 MPa) and group 5 (5.30 MPa). These values reduced to 0.18 ± 0.02, 0.15 ± 0.04, 0.19 ± 0.06, 0.28 ± 0.05 and 0.30 ± 0.07 µm, respectively (figure 5). The changes in the surface roughness of the pin groups were found to be significant; they all returned a p-value of 0.00.

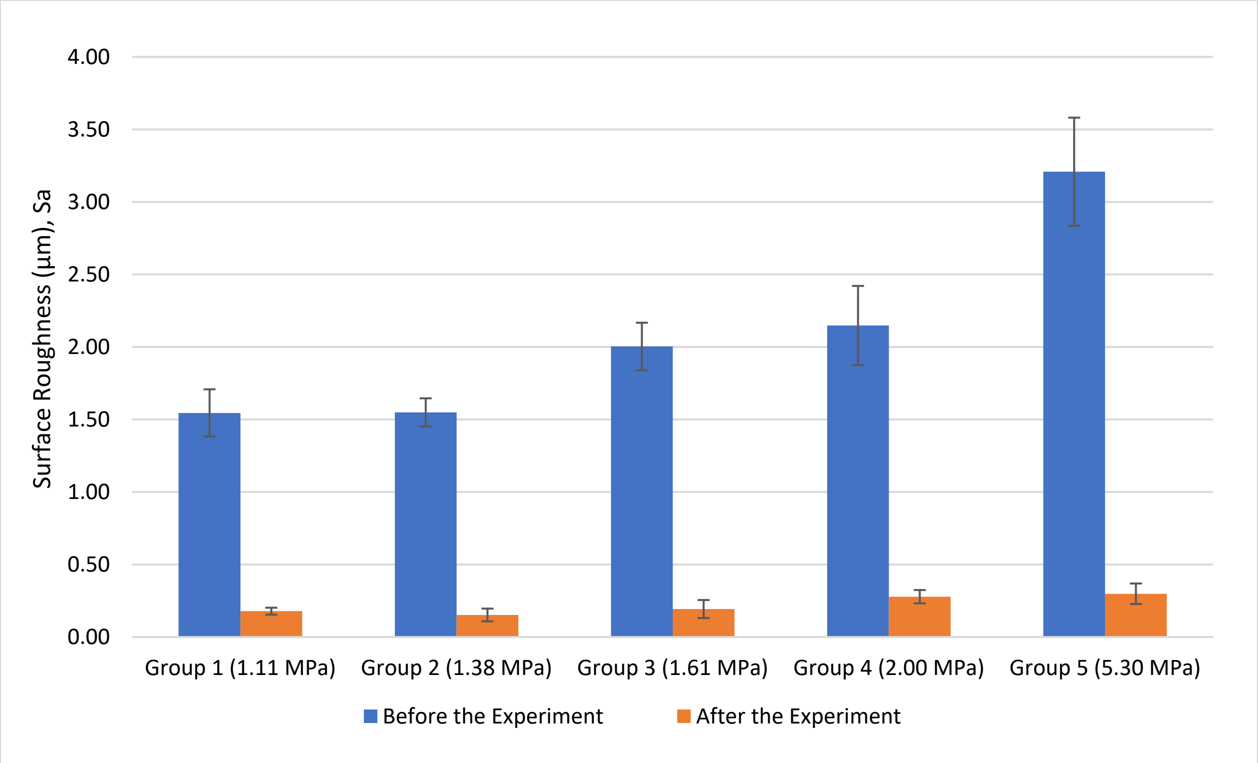

Figure 5 Surface roughness of the pin groups before and after the experiment.

Two pins from group 5 (5.30 MPa) snapped in the first 500,000 cycles and 1,000,000 cycles respectively. This was not observed for the other pin groups at any stage.

Calculated wear rates and wear factors of the CoCr discs are given in table 5.

Table 5 Summary of the wear rates and wear factors of the disc groups

Test pin group	**Wear Rate (mg/Mc) ± SD**	**Wear Factor (mm^3/Nm) x10^{-8} ± SD**
Group 1 (1.11 MPa)	1.32 ± 1.34	6.51 ± 6.59
Group 2 (1.38 MPa)	1.17 ± 0.91	5.78 ± 4.51
Group 3 (1.68 MPa)	0.73 ± 0.34	3.60 ± 1.70
Group 4 (2.00 MPa)	1.63 ± 1.01	8.02 ± 5.00
Group 5 (5.30 MPa)	1.42 ± 1.03	7.00 ± 5.06

Mc: million cycles, SD: standard deviation

The change in the average weight of the CoCr discs is given in figure 6. At the end of the experiment, a total of 3.12 mg of material was removed from the surfaces of the 50 discs in comparison to 10.50 mg of material removal from 50 pins (the weight losses were 3.97, 1.72, 1.52, 1.67 and 1.63 mg for groups 1-5 respectively).

Comparing the final weight to the initial weight, the changes in weight of each disc was found to be significant (ANOVA, p=0.000). Group-wise statistical comparison also returned p-values of 0.018, 0.001, 0.000, 0.000, and 0.006, that were all significant, for group 1 (1.11 MPa), group 2 (1.38 MPa), group 3 (1.61 MPa), group 4 (2.00 MPa) and group 5 (5.30 MPa), respectively.

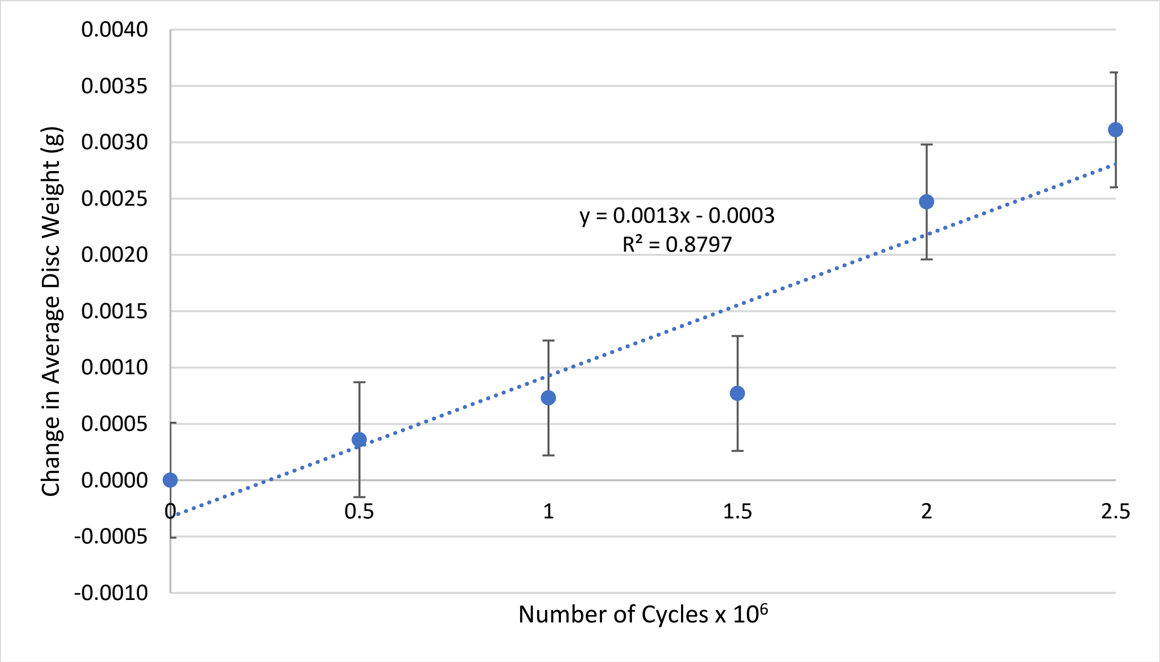

Figure 6 Changes in the weights of the discs (positive is weight loss) with respect to the number of cycles.

On average, the surface roughness of the discs prior to the experiment was measured as 0.015 ± 0.004 µm, and this value increased to 0.020 ± 0.005 µm, at the end of 2.5 million cycles (figure 7). The change in surface roughness was statistically significant (p=0.001), however, after the first 500,000 cycles, the change was not significant (p=0.85). The change in surface roughness of the groups compared to their initial values were found to be insignificant after the first 500,000 cycles. P-values were calculated as 0.112, 0.687, 0.258, 0.108, 0.257 for group 1 (1.11 MPa), group 2 (1.38 MPa), group 3 (1.61 MPa), group 4 (2.00 MPa) and group 5 (5.30 MPa), respectively.

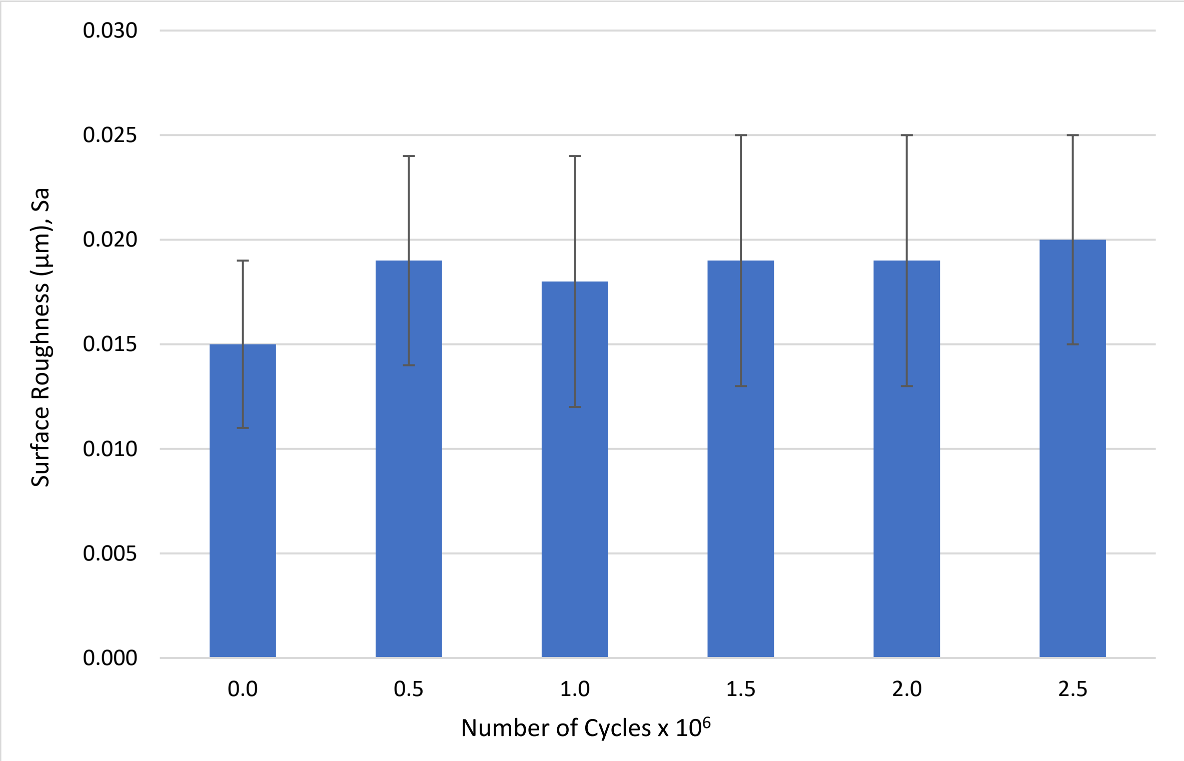

Figure 7 Average surface roughness values of the discs with respect to the number of cycles.

Discussion

The wear behaviour of CFR PEEK was investigated using a high capacity wear tester and the results showed no correlation between calculated wear factors and varying contact stresses within the clinically relevant range. In contrast, the wear rates of UHMWPE and XLPE both changed with varying contact stresses. Specifically, their wear rates were found to be lower at higher contact stresses [16, 26]. In this study, for the contact stresses of 1.11, 1.38. 1.61, 2.00 and 5.30 MPa, wear factors of 0.42, 0.19, 0.18, 0.17 and 0.19 x 10^{-6} $\frac{mm^3}{Nm}$ for the test pins were calculated. Our results for group 4 (2.00 MPa) showed good agreement with Scholes and Unsworth [24]'s study in which they tested four CFR PEEK pins tested at 2.00 MPa, and calculated a wear factor of 0.21 x 10^{-6} $\frac{mm^3}{Nm}$. In addition to this, the controls pins used in this study showed almost one order of magnitude higher weight gain than the equivalent XLPE pins [16]. Other studies of CFR PEEK have also shown its relatively high fluid uptake, especially at the beginning of wear testing [34, 35]. The relatively higher rate of fluid absorption is said to be due the fact that CFR PEEK requires a longer period of time to reach an equilibrium in lubricant absorption than polyethylene materials [36].

As shown in figure 4, the wear of group 1 (1.11MPa) was significantly different to the other groups. However, in this group, three of the pins showed a different wear behaviour compared to the other seven pins. In [24], Scholes and Unsworth also measured a significantly higher volumetric wear for one of the four pins that they tested for 2 million cycles against CoCr. The pin was found to produce higher wear every time the experiment was stopped for measurements, similar to what was observed for the three pins from group 1 (1.11 MPa).

For interest, the wear rate of group 1 was calculated again by excluding those three pins. This resulted in an average wear rate and an average wear factor of 0.56 ± 0.32 $\frac{mg}{Mc}$ and 0.17 ± 0.10 $\frac{mm^3}{Nm}$ for group 1 (1.11 MPa) pins. The statistical comparison (ANOVA) of this wear rate value with the wear rates of other groups returned a p-value of 0.92 which indicated that the difference between the wear rates of the groups was insignificant. A similar result, namely consistent wear factors at different contact stresses, was found by Evans et al.[25] for CFR PEEK pins articulated against ceramic under contact stresses below 6 MPa.

Two pins from group 5 (5.30 MPa), the group that had the highest contact stress, snapped in the first and second 500,000 cycles respectively, see figure 8.

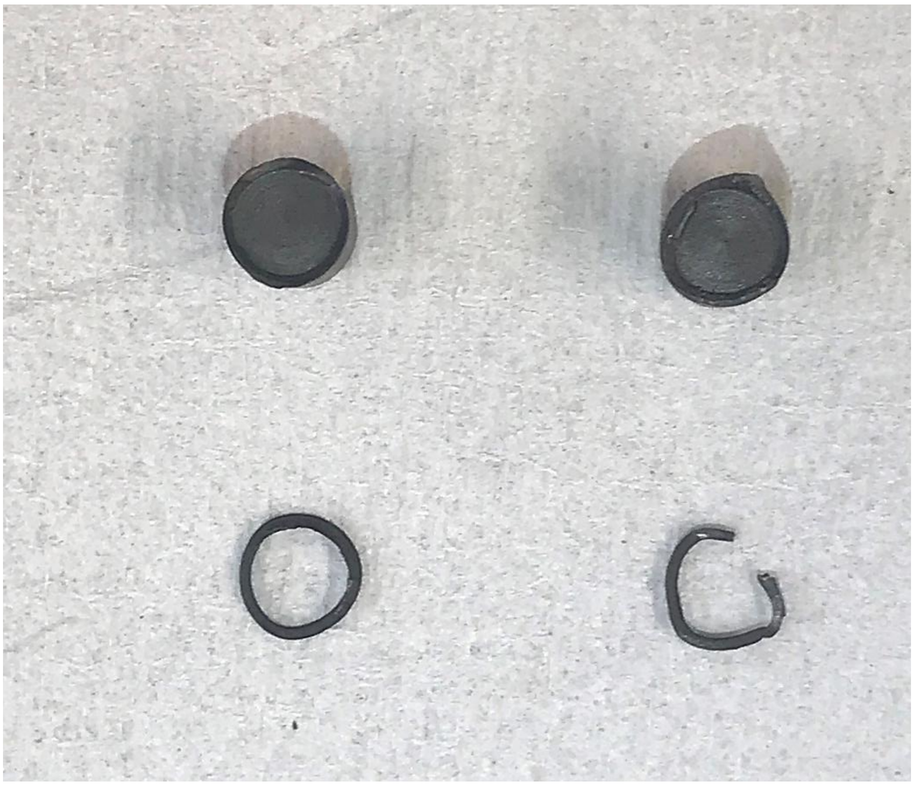

Figure 8 Snapped pins from group 5 (5.30 MPa). The one on the left hand-side snapped in the first and the one on the right hand-side snapped in the second 500,000 cycles, respectively.

When the experiment stopped at these intervals, the assemblies that these two pins articulated against were checked. No problem was detected: the assemblies were in the correct positions within the test bath and there was lubricant remaining inside the assemblies. The snapping of those two pins, may raise some concerns in terms of CFR PEEKs ability to support the stresses acting on it, especially at relatively higher stresses because the same problem was not observed for the other pin groups. Approaching the tribological endurance limit [37] of CFR PEEK might have caused these two pins to snap. Another reason might be the initial surface roughness values of group 5 (5.30 MPa) pins. As given in the Materials and Methods section, group 5 (5.30 MPa) pins had the highest initial average surface roughness (3.17 μm), compared to the other pin groups. This might have caused those two pins to snap at the beginning of the experiment while the surfaces of the pins were relatively rougher. However, to understand whether this has affected the data we collected, further research is required. As future work, we will further investigate this hypothesis.

Another different finding for CFR PEEK pins compared to XLPE and UHMWPE, and possibly the most important finding of this paper, was the wear of the CoCr discs that articulated against them. The weight losses from the discs were found to be significant (ANOVA, p-value: 0.00). This is in contrast to tests of UHMWPE and XLPE where no such wear of the CoCr discs was seen [15, 16]. In fact, the average wear factor of the CoCr discs, 61.8 x $10^{-9} \frac{mm^3}{Nm}$ (table 5), is greater than that for 50 mm diameter MoM hips tested in a simulator, where 2.1 x $10^{-9} \frac{mm^3}{Nm}$ was reported [38], under adverse conditions, however, the wear rate of the MoM hips can increase up to two orders of magnitude [37]. Clinically, the release of such metal debris would likely be a concern, with the potential for local and systemic changes [39, 40].

From a tribological point of view, CoCr was chosen as the material for the femoral heads of hip prostheses due to its relatively high hardness values [41]. Having high hardness values makes it scratch resistant and therefore reduces the possibility of metal ion release from the articulation to the surrounding tissues. The hardness of UHMWPE is recorded as 31 MPa by Diaz and Fuentes [42]. The hardness of the XLPE pins tested in [16] was measured as 60 MPa. As given in table 2, the hardness of the CFR PEEK is 298 MPa (PEEK's hardness (220 MPa [42]) is enhanced by carbon fibres) which is almost 10 times more than UHMWPE and 5 times more of XLPE. The hardness of the CoCr on the other hand, is said to vary from 550 MPa to 800 MPa [43]. However, the CFR PEEK pins were able to scratch the CoCr disc surfaces during testing. The wear track on the surfaces of the discs (see figure 9) and the significant drop in their weight were indicatives of this. Thus, if CFR PEEK was used as the material of an acetabular liner, it could wear a metallic femoral head.

Figure 9 A sample worn test disc after 2.5 million cycles of testing showing a central oval worn area.

The weight loss of the discs indicated that there was metal debris release. Such metal debris generation has been a serious issue for MoM hips [27], however, in this study; it was observed for the articulation of a polymer against a metal. As shown in the current paper, as well as in historical work on CFR UHMWPE, and by East et al. [44], carbon fibres can abrade the counterface. Thus, adding fillers to orthopaedic polymers may initiate problems and should be approached with caution.

If the wear behaviours of XLPE and CFR PEEK against CoCr were compared with UHMWPE, it can be seen that both of these materials were more wear resistant than UHMWPE (Figure 10). The wear rates were found to be 0.56, 7.86 [15], and 1.05 [16] $\frac{mg}{Mc}$ for CFR PEEK, UHMWPE and XLPE, respectively. Although the weight loss from CFR PEEK pins were lower than XLPE pins at the end of the experiment, two of the test pins from group 5 (5.30 MPa) broke and an unexpected wear behaviour was observed for three of the pins of group 1 (1.11 MPa). In addition, for UHMWPE and XLPE, no significant difference was recorded for the change in weight of the discs [16, 45]. In contrast, CFR PEEK was seen to cause wear of the CoCr discs.

For these reasons, XLPE would likely be better than CFR PEEK as a material for an acetabular liner.

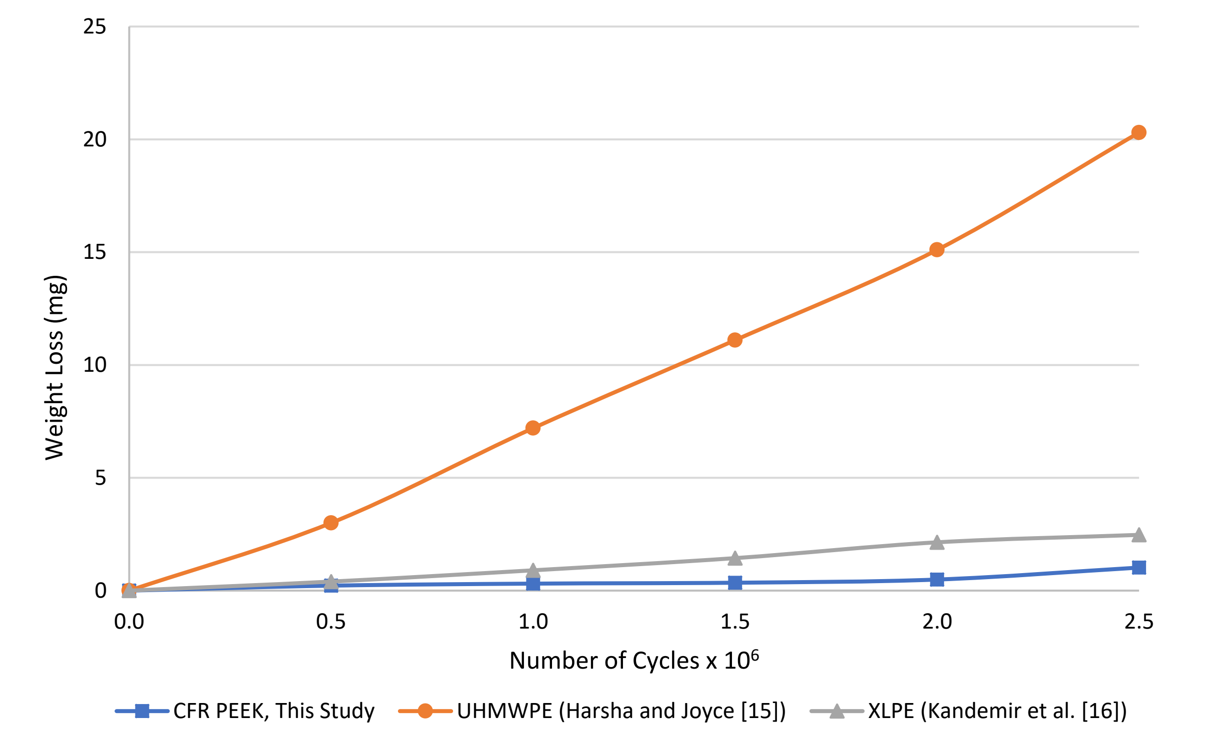

Figure 10 Comparison of the wear behaviours of CFR PEEK, UHMWPE and XLPE tested under a contact stress of 1.11 MPa with SuperCTPOD.

At the end of the experiment the surfaces of the test pins, regardless of the contact stresses they were tested at, were all burnished. This was observed by other researchers as well [14, 24]. The change in the surface roughness values was found to be significant (p=0.00). In addition, when the final average surface roughness values of the groups were compared (see figure 5), it was seen that group 5 (5.30 MPa) had the highest surface roughness value and the surface roughness values followed an increasing trend between the groups. The same behaviour was observed for XLPE test pins at the end of a similar experiment [16].

CFR PEEK articulating against CoCr is not a suitable option to be used in orthopaedics.

Conclusion

It was found that varying contact stresses within the clinical range did not significantly affect the wear of CFR PEEK when articulated against CoCr. Even though the wear rates were found to be lower than UHMWPE and XLPE, it was disconcerting to find that the two of the pins (tested at 5.30 MPa) snapped, and at the end of the experiment, three of the pins (tested at 1.11 MPa) showed unexpected wear behaviour. In addition, the pins wore the CoCr discs. CFR PEEK against CoCr cannot be recommended as a material combination in orthopaedics.

Acknowledgements

The experiment was carried out in the School of Engineering at Newcastle University.

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