

# The influence of third-body particles on wear rate in unicondylar knee arthroplasty: a wear simulator study with bone and cement debris

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**Abstract** The reduced intraoperative visibility of minimally invasive implanted unicondylar knee arthroplasty makes it difficult to remove bone and cement debris, which have been reported on the surface of damaged and retrieved bearings. Therefore, the aim of this study was to analyze the influence of bone and cement particles on the wear rate of unicompartamental knee prostheses in vitro. Fixed bearing unicompartamental knee prostheses were tested using a knee-wear-simulator according to the ISO standard 14243-1:2002(E) for 5.0 million cycles. Afterwards bone debris (particle size  $671 \pm 262 \mu\text{m}$ ) were added to the test fluid in a concentration of 5 g/l for 1.5 million cycles, followed by 1.5 million cycles blended with cement debris (particle size  $644 \pm 186 \mu\text{m}$ ) in the same concentration. Wear rate, knee-kinematics and wear-pattern were analyzed. The wear rate reached  $12.5 \pm 1.0 \text{ mm}^3/\text{million}$  cycles in the running-in and decreased during the steady state phase to  $4.4 \pm 0.91 \text{ mm}^3/\text{million}$  cycles. Bone particles resulted in a wear rate of  $3.0 \pm 1.27 \text{ mm}^3/\text{million}$

cycles with no influence on the wear rate compared to the steady state phase. Cement particles, however, lead to a significantly higher wear rate ( $25.0 \pm 16.93 \text{ mm}^3/\text{million}$  cycles) compared to the steady state phase. The careful removal of extruded cement debris during implantation may help in reducing wear rate. Bone debris are suggested to have less critical influence on the prostheses wear rate.

## 1 Introduction

Pathologies such as medial compartment osteoarthritis and Ahlbaeck's disease, as well as therapy applications such as high tibial osteotomy, lead to a constant increase in implantation of unicompartamental knee arthroplastys (UKA) [1].

UKA offers advantages over total knee arthroplasty (TKA) as a primary procedure because it allows sparing of soft-tissues, potentially leading to better tibiofemoral and patellofemoral kinematics [2] and range of motion [3]. Furthermore, the minimally invasive implantation technique is believed to induce less soft tissue trauma, in particular because it does not require eversion of the patella, thus avoiding damages to the prepatellar bursa. It was also reported that UKA patients suffer less blood loss, reduced perioperative morbidity and faster rehabilitation than TKA-patients [4, 5]. Another important advantage is that, as it is less invasive than TKA as a primary procedure, it still offers the possibility for a successful implantation of TKA in cases of revision [6].

While the 10-year-survival rates of UKAs have been shown to be equivalent to those of modern TKA [7], clinical evidence has demonstrated a higher revision rate of UKA compared to TKA [8]. This may be due to lack of sufficient experience to implant such prosthesis with

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minimally invasive approaches [9, 10]. Due to the small operative field and the absence of anatomical landmarks, the accurate positioning of the prostheses is more difficult [4]. Third-body wear like cement and bone fragments are also believed to influence the wear behaviour and might represent one mechanism for accelerated wear and early failure of the prostheses [11]. Such fragments can easily go unnoticed during a minimally-invasive UKA implantation because the posterior regions of the femoral and tibial components remain difficult to inspect for extruded cement or impinged soft tissue. While this is evidenced by clinical reports and retrieval studies where free cement and bone debris were found in joints of patients with minimal invasive implanted UKA [12], so far the role of third-body debris on the wear in UKA was not investigated.

Therefore, the aim of this study was to analyze the influence of third-body wear debris such as bone and cement particles on the wear rate and wear pattern of unicompartamental knee arthroplasties. We first hypothesize that an occurrence of third-body debris can lead to increases in wear rate and change of wear patterns. Our second hypothesis is that bone debris can also affect the in vitro wear rate. Our third hypothesis is that the presence of debris may alter tibio-femoral kinematics of the implanted UKA.

## 2 Material and methods

### 2.1 Prostheses

For this analysis, fixed bearing unicompartamental knee prosthesis (Univation-F, Aesculap, Tuttlingen, Germany) was used with a metal-polyethylene articulation.

The intermediate-sized femoral and tibial (F3/T4) components were made out of CoCr29Mo6 alloy and the gliding inserts were composed of UHMWPE (GUR 1020,  $\gamma$ -irradiated,  $30 \pm 2$  kGy).

The inserts were fixed at the tibial baseplate component by a snap-fit-mechanism. The medial side of the meniscal bearing had a concave shape and the lateral side was planar. Before testing, the bearings were accelerated aged, according to the standard (ASTM F2003-02(2008)).

### 2.2 In-vitro wear testing specifications

Before wear testing the gliding surfaces were conditioned in the test solution until no increase of weight was measurable. The test fluid simulated synovial liquid with a protein content of 30 g/l. It consists of new born calf serum (Biochrom, Germany) diluted with EDTA (AppliChem, Germany) for pH stability and Amphotericin B (Biochrom, Germany) as a fungicidal.

**Table 1** Size and shape of third-body particulate debris

Parameter	Bone debris	Cement debris
Mean diameter ( $\mu\text{m}$ )	$671.6 \pm 186.4$	$644.2 \pm 262.6$
Equivalent circle diameter ( $\mu\text{m}$ )	$519.0 \pm 142.9$	$548.4 \pm 237.3$
Form factor	$0.41 \pm 0.12$	$0.57 \pm 0.12$
Aspect ratio	$1.74 \pm 0.62$	$1.74 \pm 0.70$
Roundness	$0.50 \pm 0.14$	$0.42 \pm 0.14$

The specimens were tested on a servo-hydraulic knee wear simulator (EndoLab, Germany) with four test stations. A prescribed walking gait pattern and physiological loading described by ISO 14243-1:2002(E) was applied on three of the four specimens, while the remaining specimen was used as a load-soak control. Testing was stopped at 8.0 million cycles (MC) and divided in three parts. The first part was a standard test with 5.0 MC as described in the ISO 14243-1:2002(E). In the following two parts, the test solution was contaminated with third-body wear debris in a concentration of 5.0 g/l and then the specimens were tested for 1.5 MC in the wear simulator. The particles were manufactured by a micro bone mill (Aesculap GB060R, Tuttlingen, Germany). The size and shape of the third-body debris, measured by scanning electron microscopy, are shown in Table 1. Between 5.0 and 6.5 MC the third-body wear particles were cortical porcine bone particles (Fig. 1, left). Subsequently, from 6.5 to 8.0 MC, cement particles with zirconiumdioxide as radiolucent (Palacos R, Heraeus Medical, Germany) were placed in the test solution for the final part of the test (Fig. 1, right).

### 2.3 Gravimetric measurement and kinematic data analysis

At every 500,000 cycles the test serum was changed and the prostheses were cleaned gently according to a standardized cleaning protocol (ISO 14243-2:2000(E)). Afterwards, the inserts were weighted with an accuracy of  $\pm 0.01$  mg (Sartorius BP211D, Germany) and their masses corrected with the load-soak control and air buoyancy.

The gravimetric wear rate was calculated as described in the ISO 14243-2:2000E and was converted to volumetric wear rate ( $a_v$ ) using the density of UHMWPE (density of GUR1020 is  $\rho = 0.932$  g/mm<sup>3</sup>) [13], according to the following equation:

$$a_v = \frac{a_m}{\rho}$$

To evaluate the effects of third-body wear on the bearing mechanism of the UKA implants, the prostheses' tibio-femoral anterior/posterior (AP) translation and the internal/external (IE) rotation were measured, analyzed



**Fig. 1** Third-body debris in the test chamber without test fluid. On the *left side* the bone fragments and on the *right side* the cement debris is shown

[14] and reported in terms of maximum for each test period.

At the end of every test period, the inlays were scanned parallel to the wear surface with 300dpi (Epson Expression 1680Pro, USA) and also analyzed with a reflected light microscope (Leica MZ12, Germany).

### 2.4 Statistics

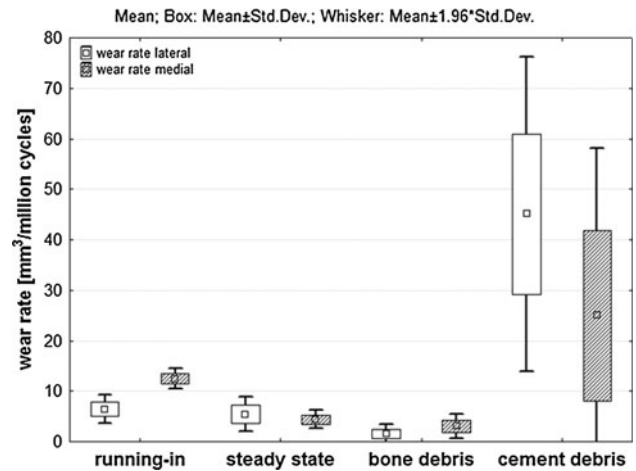
The measured data were classified in four groups: running-in, steady state, bone- and cement debris. The first group describes the running-in of the prostheses and was defined between 0.5 and 2.0 MC. In this range the steady state was adjusted and calculated between 2.0 and 5.0 MC. Afterwards, the two-third-body wear groups were tested like described before.

A Kolmogorov–Smirnov test was carried out to verify normal distribution, followed by direct comparisons to differentiate the volumetric wear amount and prostheses kinematics between the gliding surfaces using a ANOVA followed by a Duncan post hoc test (Statistica 9.1, StatSoft, USA). The statistical significance level was set to  $P = 0.05$ . All data is presented as mean and standard deviation of the mean ( $\pm$ ).

## 3 Results

### 3.1 Wear rate

The volumetric wear rates of the medial and lateral UHMWPE-inserts are shown in Fig. 2. During the running-in phase the wear rate of the medial inserts was  $12.5 \pm 1.0 \text{ mm}^3/\text{MC}$  and in the steady state phase  $4.4 \pm 0.9 \text{ mm}^3/\text{MC}$  ( $P = 0.27$  to running-in phase). The wear rate after bone particle contamination was  $3.0 \pm 1.3 \text{ mm}^3/\text{MC}$  ( $P = 0.85$



**Fig. 2** Volumetric wear rate of the medial and lateral specimens in box plots comprising the mean and standard deviation of the four groups

to steady state). After cement particles contamination the wear rate increased significantly to  $25.0 \pm 16.9 \text{ mm}^3/\text{MC}$  ( $P = 0.02$  to steady state and bone particle phase).

For the lateral side, the wear rate in the running-in phase was  $6.4 \pm 1.4 \text{ mm}^3/\text{MC}$  and in the steady state phase was  $5.4 \pm 1.8 \text{ mm}^3/\text{MC}$  ( $P = 0.88$  to running-in phase). After bone particles contamination, the wear rate was  $1.52 \pm 1.0 \text{ mm}^3/\text{MC}$  ( $P = 0.49$  to steady state), with a significant increase to  $45.0 \pm 15.9 \text{ mm}^3/\text{MC}$  after cement particles contamination ( $P = 0.0005$  to running-in and steady state group;  $P = 0.0003$  to bone particle group). The cumulative wear volume of the tested specimens are shown in Fig. 3.

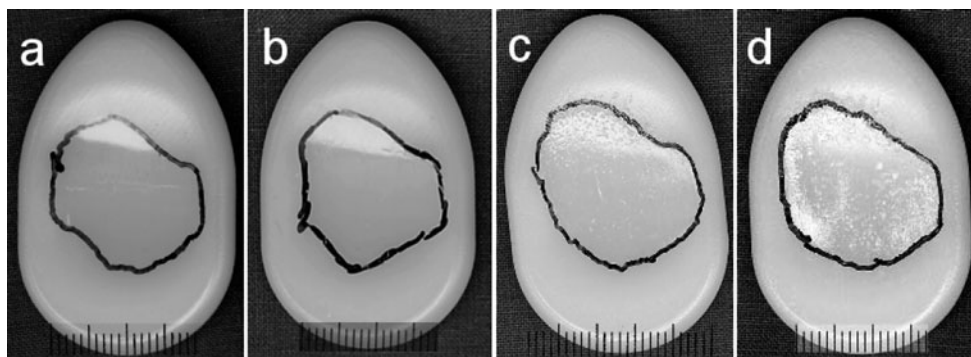
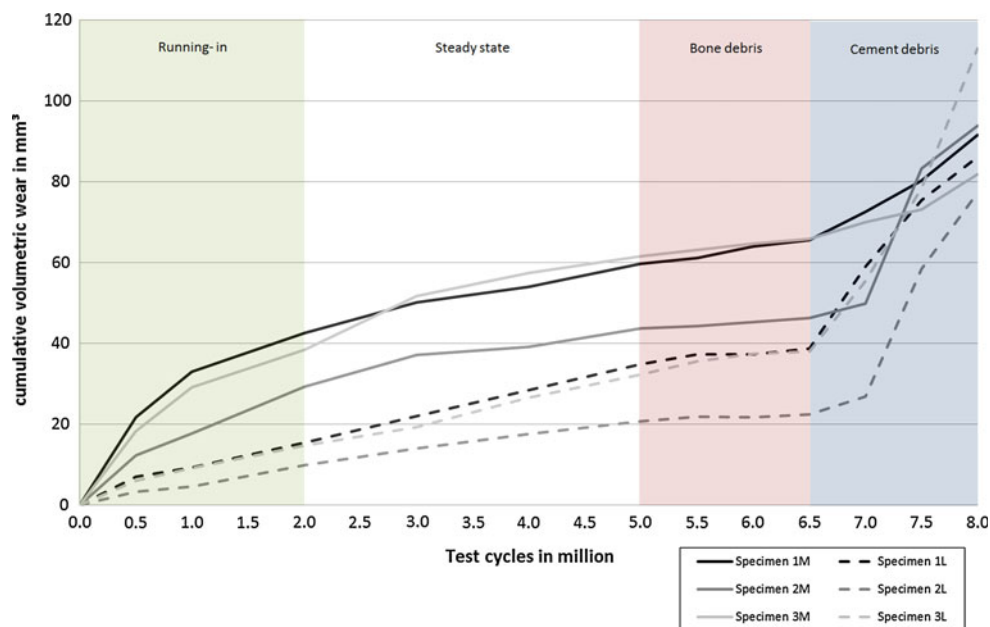
### 3.2 Wear pattern

At the running-in-phase (Fig. 4a), some burnishing and scratches were found as well as in the steady state (Fig. 4b). After adding bone debris, severe pitting and embedded debris were found (Fig. 4c). Contaminating the test fluid with cement particles resulted in massive abrasion, pitting and deep scratches on the bearing surfaces (Fig. 4d). Burnishing was nearly completely replaced by abrasion and rough surfaces (Fig. 5).

### 3.3 Kinematics

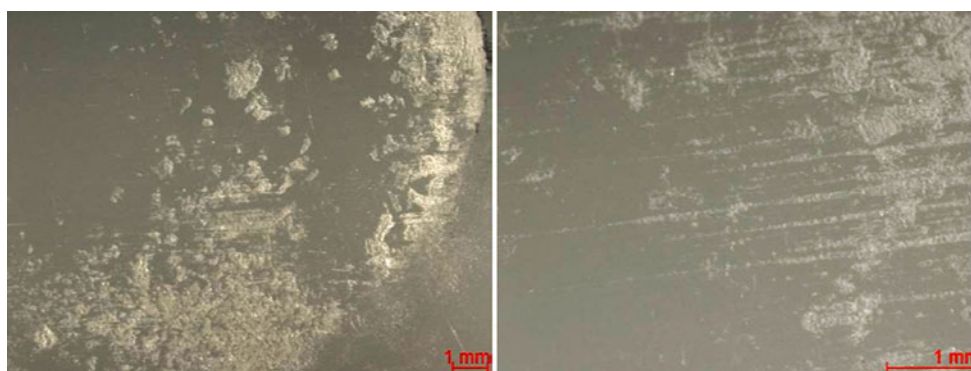
The AP-translation of the running-in phase was  $4.54 \pm 0.12 \text{ mm}$  and the IE-rotation of the prostheses is  $5.61 \pm 0.15^\circ$ . Both the AP-translation ( $P = 0.0002$ ) and the IE-rotation ( $P = 0.0002$ ) were significantly higher compared to the steady state phase (Fig. 6). The steady state phase was characterized by an AP-translation of  $3.56 \pm 0.09 \text{ mm}$  and an IE-rotation of  $4.37 \pm 0.08^\circ$ . By adding bone particles to the test medium, the AP-translation

**Fig. 3** Cumulative wear of the tested specimens



**Fig. 4** Medial gliding surface scanned with a 1 mm scale after every test phase. **a** Running-in: basically polishing and small scratches were observed. **b** Steady state: in addition to the running-in more scratches and small pittings were found on the surface. **c** Bone debris: severe

pitting was shown on the anterior parts of the specimens. Burnishing, scratches and embedded debris were found. **d** Cement debris: all the specimens show a rough surface, abrasion, less burnishing and severe pitting



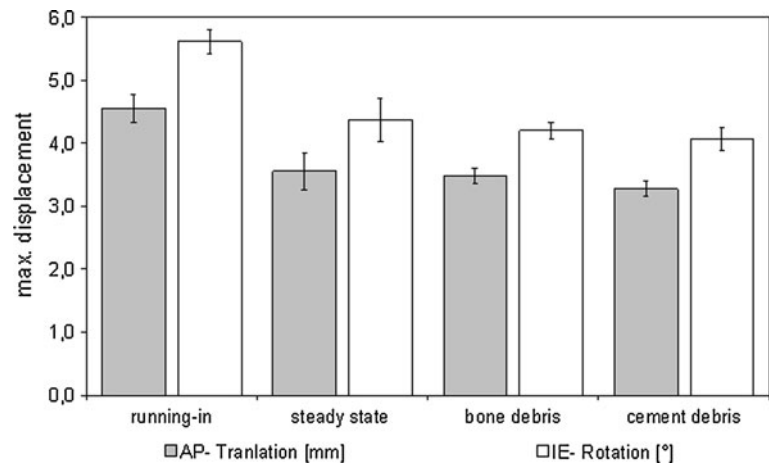
**Fig. 5** The wear surface after 8.0 million cycles under a reflected light microscope. Severe pitting, burnishing and abrasion was observed in the left picture. The right photo shows deep scratches and pittings

$3.48 \pm 0.14$  mm ( $P = 0.5$ ) and IE-rotation  $4.20 \pm 0.14^\circ$  ( $P = 0.2$ ) were not changed compared to the steady state. The same behavior shows the test with cement debris with

an AP-translation of  $3.27 \pm 0.14$  mm ( $P = 0.2$ ) and an IE-rotation of  $4.07 \pm 0.12^\circ$  ( $P = 0.1$ ). Knee kinematics, however, changed significantly between the steady state



**Fig. 6** Comparison of the maximum internal/external rotation and anterior/posterior translation of the complete UKA prostheses during the four test groups



and cement particle phase (IE:  $P = 0.02$ ; AP:  $P = 0.03$ ) (Fig. 6).

#### 4 Discussions

This study demonstrated that free cement debris can significantly increase the wear rate in unicondylar arthroplasty. Many case reports as well as clinical and retrieval studies have shown that third-body debris can be frequently found in the articulation space of UKA [12, 15]. Only Reich et al. [16] described a test setup including bone and cement debris on ZrN coated TKA, but only reporting the stability of the ZrN-layers under abrasive conditions and without reporting wear rates after the inclusion of third-body debris.

Our objective was therefore to analyze the wear behavior of a fixed bearing UKA under the influence of third-body debris like cortical bone and cement in terms of wear volume, surface damage and prostheses kinematics.

The third-body wear particles were selected as described by De Baets et al. [17]. These authors demonstrated that bone and cement debris were found in the joint space during and after the implantation of a TKA. Wang and coworkers analyzed the influence of third-body wear on hip replacements and found out that a concentration less than 3.0 g/l did not influence the wear rate of hip arthroplasties in wear simulators. Therefore a high contamination of 5.0 g/l (1.2 g per test chamber) was chosen as described for knee [16] and for hip wear analysis [11]. This concentration is approximately 25 times higher for cement and 20 times higher for bone debris compared to findings in TKA during surgery [17]. For comparison, bone and cement debris have similar ranges of particle-diameters and comparable shape parameters (Table 1).

Because of the comparably low congruency of these designs, the accelerated aged gliding surfaces, and the high

debris concentrations, clear results were expected regarding the inclusion of debris particles on the wear rates.

Effectively, our results demonstrated that the wear rates of the tested specimens with cement debris contamination in the test fluid were significantly higher than for the steady state phase. Consequently, we were able to prove our first assumption, that cement debris increase the wear rate in UKA in vitro. However, as there were no significant differences between the group with bone debris contamination and the steady state phase, this contradicts our second hypothesis that bone debris contamination can influence the wear rate of UKAs in vitro. Additionally, the kinematic analysis showed a significantly larger AP-translation and IR-rotation in the running-in phase compared to the other phases. While only the cement group generated a significantly lesser AP- and IE-motion compared to the steady state, it also validated our final hypothesis that the presence of debris, irrespective of their type, may have an impact on resulting kinematics.

These results must be confronted to previously published work on UKA. The wear rate of the running-in phase is directly comparable to the study from Spinelli et al. [18]. These authors tested a round-on-flat UKA in a wear simulator for 2.0 MC, and reported average wear rates of 10.3 mg/MC for the medial side and 4.5 mg/MC for the lateral side. During the running-in phase, the femur component carved to the UHMWPE-bearing, therefore the AP-translation and IR-rotation of the prostheses decreases over the 2.0 MC [18, 19], a trend which was also observed in our study.

Regarding the difference between medial and lateral wear rates without third-body wear particles, our results differ in part from earlier reports. For instance, Laurent et al. and other groups described a significant higher wear rate on the medial compared to the lateral specimens over 5.0 MC [14, 18, 20]. While our results show similar trends in the running-in phase, at the steady state phase, however,

no difference in wear rates could be observed between the lateral versus medial sides.

Our study setup could successfully show the increased wear rates following the inclusion of cement particles in UKA wear. In bone cement, adamant substances like zirconiumdioxide or barium sulfate were used as radio-opaque substances. Our results show that cement particles with zirconiumdioxide as radio-opacifier can increase the wear rate seven times compared to the steady state phase. Zirconiumdioxide is a harder material with a lesser solubility than barium sulfate. Therefore zirconiumdioxide is more harmful than barium sulfate. However, bone cement containing barium sulfate is involved with a higher rate of osteolysis than zirconiumdioxide [21, 22]. A similar increase of the wear rate by hip prostheses with a CoCrMo–UHMWPE articulation under cement contamination was also previously reported [11]. The abrasive-acting cement particles more significantly increased the wear rate for the round-on-flat bearing mechanism of the lateral insert compared to the medial specimen, leading to decreased AP-translation and IE-rotation as the femoral component carved into the UHMWPE-surface [19]. The abrasion and deep pitting which could be observed on the wear surface of the specimens were also consistent with retrieval reports for UKA [12, 15].

On the other side, contamination with bone debris did not influence the wear rate of the UHMWPE-inserts compared to the steady state. Severe pitting and embedded debris on the surface of the gliding insert suggest that bone particles may have penetrated in the UHMWPE-material and operated as a spacer between the femoral component and the tibial insert, leading to a therefore constant wear rate. Additionally, the organic components in the bone debris like collagen and proteins are able to act as a lubricant. However, damage to the UHMWPE-surface, in part due to the expected higher Herzian-stresses between the bone debris and the gliding surface, cannot be excluded. Based on their higher ductility, lower hard- and brittleness, the used bone debris have a lesser abrasive effect compared to the cement debris.

Our study contains some limitations which must be carefully considered in the clinical interpretation of the results. Firstly, wear simulation tests were performed in a single series of 8.0 MC divided in four test groups, rather than different series testing each scenario. This was considered an adequate approach because the embedment of the prostheses and alignment of the specimens in the test rig were both rigorously maintained, and that identical force-control parameter over the whole test period could be insured, allowing identical test conditions for all groups. Secondly, it cannot be claimed that the bearings would have been damaged or not by adding bone particles in the test chamber before adding the cement particles, as the current study setup was not randomized for particle type

and was performed with including bone particles after the inclusion of cement particles. However, because wear rate and kinematics were not changed after adding bone particles compared to the steady state, we assumed only negligible changes of the wear pattern could be caused by bone debris. Furthermore, the third-bodies were added within the stable steady state of the specimens, after the running-in phase where wear often shows a higher variability. It was therefore expected that the steady state phase could be used as a reference and could allow an independent calculation of wear rate for each of the third-body groups.

Thirdly, the prosthesis used in this study is only designed for medial UKA. In order to have a controlled condition for the lateral side, a flat insert was chosen for the lateral side. The choice of flat surface was based on the fact that for the lateral compartment, many prostheses in use a round-on-flat bearing mechanism [18, 20], which is believed to allow for a physiological kinematic pattern driven by the anterior and posterior cruciate ligaments and the untreated lateral condyle. Nevertheless, additional tests with other types of lateral bearing surfaces may reveal different trends, but this remains to be investigated.

One final limitation is that the simulator only mimicked level walking, Activities of daily living like stair climbing, chair-rising, squatting, may also influence wear behavior in vivo. Despite these limitations, we believe that this study offers a valuable insight into the role of debris in wear of the UHMWPE-components in UKA.

## 5 Conclusion

Our in vitro data suggests that careful removal of extruded cement debris during implantation may help in reducing wear rate. Ideally, X-ray diagnosis should be used to localize and remove hidden cement debris. Additionally, free bone debris, for instance those generated by sawing during the implantation, had a lesser impact on the wear rate of UKA in vitro. Nevertheless, their removal should be considered too, as bone debris were observed to create pitting on the UHMWPE-bearings, which may influence the wear mechanism or lead to severe structural material fatigue in vivo [12].

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