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VOLUMETRIC WEAR ANALYSIS OF HIP JOINT IMPLANTS BY OPTICAL METHODS

ANALÝZA OBJEMOVÉHO OPOTREBENIA BEDROVÝCH IMPLANTÁTOV POMOCOU OPTICKÝCH METÓD

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1 INTRODUCTION

Total hip replacement is one of the most common surgeries in modern medicine. During the total hip replacement surgery, failed femoral head and acetabulum are extracted and replaced with artificial components. Number of these surgeries increased on average by 30 % between years 2001 and 2017. According to the *Health at a Glance* statistics published by the Organisation for Economic Co-operation and Development (OECD) [1], the increased number of total hip replacement procedures is related to changing lifestyle and age structure of population. In most cases, successful surgeries relieve the pain, however quality of life remains significantly affected. Despite many improvements, longevity of the implants is still limited to 10-20 years. Failed implants require revision surgeries with even more extensive interventions into the human body. Pelvis carrying a revised implant is more sensitive to fracture and the survival time of the revised implants is shorter than those of the primary surgeries.

Thanks to constant improvements of implants, there is a decreasing number of severe mechanical failures that require immediate revision, such as implant fracture, dislocation, or heavy delamination of the implant material. However, failures caused by aseptic loosening are increasing. Aseptic loosening is caused by osteolysis - resorption of bone tissue initialized by presence of foreign debris. Foreign particles interacting with the hip environment can cause inflammation reactions, tissue degradation and subsequent loosening of the implant. Loose implants do not provide sufficient stability and must be revised.

Certain threshold number of foreign particles released into the human body can lead to health problems. Probability of revision surgery rises with rising number of the particles. Therefore, wear reduction is identified as a high priority goal in contemporary implants research and development. To understand the implant properties and behaviour better, it is necessary to use a high performing measurement method for analysis of the retrieved cups. The thesis focused on implants composed of hard on soft materials, i.e. Metal-on-Polyethylene (MoP) and Ceramic on Polyethylene (CoP) implants.

The aim of this thesis is to provide a methodology for wear analysis of polyethylene liners on micro and macro level using optical methods. Most literature reports on a direct correlation between one input wear parameter, such as amount of wear or volume loss, and implant failures. Very few studies show a complex approach to description of geometrical and surface changes of the articulating components. For this purpose, a novel methodological approach has been developed.

2 STATE OF THE ART

There are two main approaches to wear determination: determination of *linear wear* and determination of *volumetric wear*. Volumetric wear, linear wear and wear rates are the most widely used and recognised parameters of a THR joint performance. *Linear wear* is often defined as penetration of the head into the acetabular cup and it is usually defined in relation to the lifecycle of the implant, i.e. the laboratory test results are reported in *mm per year* or *mm per number of cycles*. This approach does not consider the total volume of the released material. Liner wear analysis is not suitable for investigating the implant position or damages outside of the articulating surface [2-4]. The advantage of this method is that it is easily comparable with results of standard in vivo analyses, such as radiograph. *Volumetric wear* determines the amount of debris released from the implants. This allows for more accurate results both in terms of linear wear as well as volume of the material released into the body.

Data on linear wear, volumetric wear, wear rates and wear direction together with basic information on creep and surface changes of the implants can help us better understand the complex wear mechanism and advance our predictions of wear behaviour.

1.1.1 In vivo wear determination

Several different methods have been developed to determine wear under in vitro or in vivo conditions. Current clinical practice evaluates in vivo wear using non-destructive and contactless methods that can recognize position and shape of implants in human body. *Radiographic and stereographic examinations* are the most often used clinical routines after a total hip replacement surgery. These methods are also used for tracking the lifecycle of the implant to support medical decisions regarding arthroplasty [4-6]. *Computer tomography (CT)* is used less often. Though it provides more detailed data, including data on the surrounding environment of the implant, it is more expensive and has negative health consequences for patients [7-9].

Radiographic method is one of the clinically most widely used methods of linear wear analysis that is routinely performed with each hip replacement. The results are usually available in patients' health records. Linear head penetration is determined by image processing. One possible approach is to simply use a geometrical analysis of clear edges of implants to assess the femoral head penetration. This approach can be supported be an image processing software that recognizes the edges and calculates the wear accordingly. One of the available computer assisted techniques has been developed by Martel et al.[2]. Martell's method determines vector of wear and rate of linear wear (Fig 2.1). Martell's analysis demonstrated superior repeatability and accuracy compared to manual analysis. Better repeatability and accuracy in determination of the polyethylene wear leads to more reliable investigations of various factors influencing diagnosis of the implants.

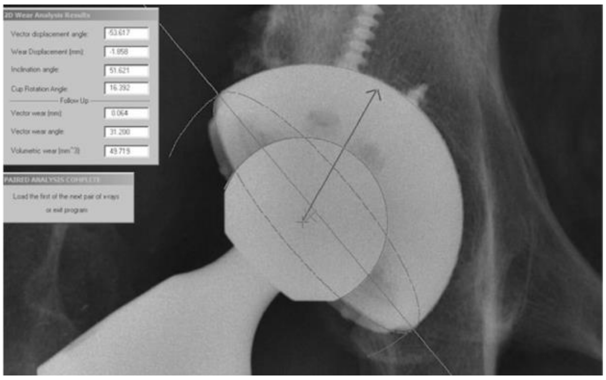


Fig 2.1 The Martell method of linear wear measurement shown on this radiograph [10].

The inherent 2D nature of many radiographic methods can cause errors in determination of wear based on implant positioning. Therefore, it is interesting to compare the results of radiographic methods with more precise methods of in vitro analysis that can provide complex information on liner surface. In vitro methods are used for retrieved liners or for wear tests on new samples. Therefore the in vitro methods as described below are used mostly for validation or for a better understanding of tribological interactions of implant surfaces.

1.1.2 In vitro wear determination

One of the frequently used methods for the articulating surface wear analysis is the *coordinate measurement method (*CMM) as described by ISO Standard 14242-2 [11]. Coordinate measuring machines are mechanical systems designed to move a measuring probe to determine coordinates of points on a surface. The machines are comprised of three main components: the machine itself, the measuring probe, and the control or computing system with a measuring software. The resulting point cloud measured with a coordinate measuring machine is post-processed using a modelling software (e.g. CAD) and regression algorithms for further analysis.

Usability of the coordinate measurement method was demonstrated by Galvin et al. [12] who compared wear of the UHMWPE acetabular cups against surface-engineered femoral heads. The wear was determined volumetrically by using a coordinate measuring machine (Kemco 400 3D, Keeley Measurement Co. UK). The three-dimensional geometry of the cups was measured before the test and then every million cycles of the wear test (Fig 2.2). Geometrical mapping allowed a three-dimensional reconstruction of the cup surface to show the maximum areas of wear and penetration.

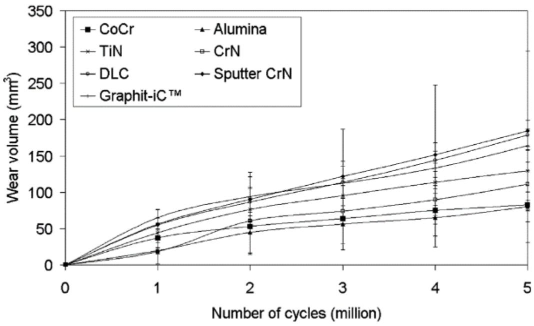


Fig 2.2 Volumetric wear of UHMWPE published by Galvin et al. [12]

Another study published by Wang et al. [13] aimed to determine volumetric wear and spatial distribution for polyethylene acetabular liners. Authors used the coordinate measurement method, (Global Classic SR 757) with probe diameter of 1mm and accuracy of 1.9 µm. The number of collected points was 3720 for each sample. The method was used on retrieved liners with no original referential surface data. The authors developed algorithms to process data from the point cloud to evaluate the volumetric wear and to determine the original geometry from the unworn area. The algorithms are equally applicable to other measuring methods.

Measurement errors of the coordinate measuring method were described by Bills et al. [14]. The study analysed the uncertainties associated with measurements of spherical geometries and applied them to both the measurement of wear in retrieved bearings and metal hip resurfacing components. The influence of measurement uncertainty was showed to be of a significant order for the coordinate measurement method. The study showed that the grid definition and performance of the meshing algorithms can significantly influence the results (Fig 2.3). It is therefore also suggested that the grid spacing should be adapted to component size. The analysis was carried out on six explanted metal-on-metal hip replacements.

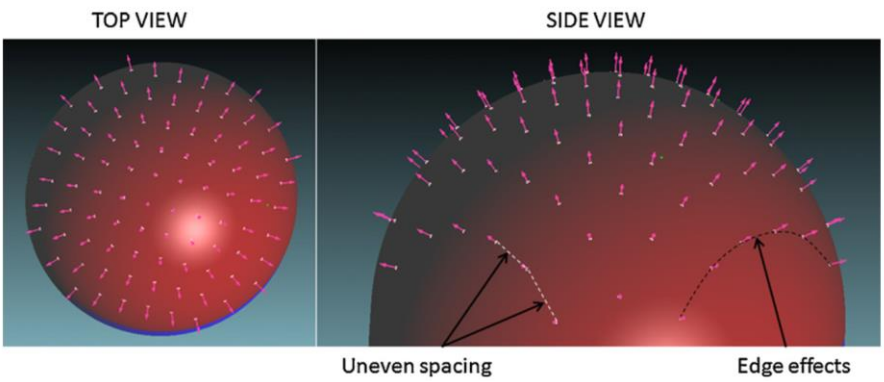
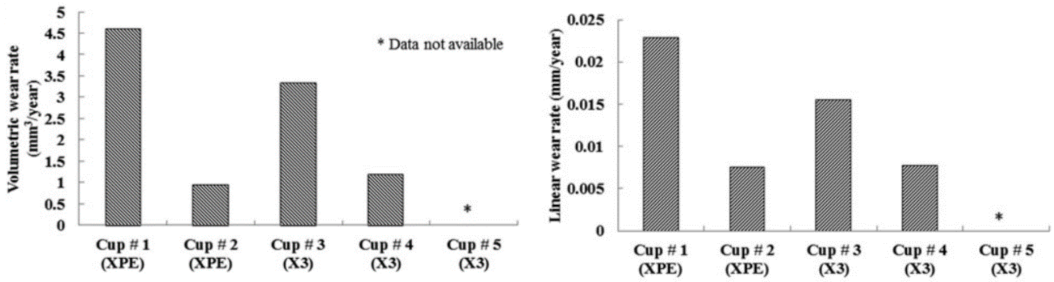


Fig 2.3 Effect of mesh spacing

The measurement error demonstrated for the volumetric wear was between 1,145 and 1,859 mm^3.

Similar principles under different measurement conditions were used for the polyethylene liners analysis by Uddin et al. [15]. The authors used the coordinated measurement method on conventional crosslinked polyethylene (XPE) and second-generation highly cross-linked polyethylene (X3) retrieved liners.

An initial coordinate measurement method probing of at least ten random points was performed on the unworn regions between the rim and the pole of the cup to define the original reference geometry. The whole worn surface of the retrieved cups was then CMM probed on predefined scanning paths with 0.25 mm × 0.25 mm mesh of measurement points to determine the worn geometry. The difference between the reference geometry and the worn geometry defined the actual wear. The results were validated with gravimetric method. The normalized error was always below 1, with maximum volumetric uncertainty of ±3.12 mm^3 (95% confidence interval, Fig 2.4) hence proving the usability of coordinated measurement method also for polyethylene surfaces.



Method	Wear Amount (mm^3) First Stage	Second Stage	Third Stage	Fourth Stage	Fifth Stage
Mean gravimetric (mg)	56	82	128	153	177
Mean gravimetric (mm^3)	7.65	10.83	16.53	19.54	22.51
Mean CMM (mm^3) (SD)	7.01 (0.81)	10.27 (0.72)	16.02 (0.62)	19.17 (0.46)	22.18 (0.29)
Normalized error, E_N	0.32	0.28	0.24	0.18	0.16

Fig 2.4 Comparison of wear rate between liners: linear and volumetric wear

1.1.2.1 Optical methods

Wear analysis methods as described above do not fully solve the problems of prosthetic wear measurement such as extensive damages and geometrical surface changes caused by significant plastic deformations or creep. Optical 3D methods and their application for quantification of the volumetric wear can be explored in this context.

The optical 3D wear measurement is based on creating a 3D profile map of a retrieved cup. A pilot study in this field was conducted by Zou et al. [16] who referred to a novel principle of optical scanning. The study described sequential hemisphere measurement method using an optical non-contact measurement system with a laser probe (OP2, Renishaw, UK) working on the principle of optical triangulation. The OP2 laser probe was designed to be used with a Motorised Probe

Head (PH9, Renishaw, UK), and held in a coordinate measuring machine (CMM, Merlin II, International Metrology System Ltd., UK). The study introduced strategy of surface alignment with a crucial influence on the complex error of volume wear determination. Zou et al. assembled partial scans, which in turn allowed analysis of the whole geometry. Reproducibility was tested on this novel approach. Volumetric differences were measured over a rectangular area of 400 mm^2 with the mean volumetric difference of 1.4 mm^3. Next, two cups were tested before and after a half million cycles wear tests and the volumetric difference was found to be 5.3 mm^3. The method also allowed to determine the direction of maximum removal of the material which is important for determining depth of femoral head penetration and linear wear. The study showed precise results, however alignment of scans during post-processing remained problematic.

Another novel approach to volumetric wear determination was introduced by Tuke et al. [17]. The method known as the RedLux Artificial Hip Profiler (AHP) (RedLux Ltd., Southampton, UK) combined the high resolution of the roundness measuring method with the high coverage of the coordinate measurement method, while using an automated, non-contact sensor for increased speed of measurements. The sensor could scan spherical objects covering the whole bearing surfaces in a single measurement taking only few minutes. The resulting cloud of points measured by the artificial hip profiler was the raw data and described the form of the sphere in 3D with a resolution of 20nm. The artificial hip profiler used a point sensor, based on the chromatically encoded confocal measurement and the method was applied on metal femoral head implants.

Tab. 2.1 Results of validation of methods [17]

Component Id	AHP measurement time (min and s)	Diameter (laser micrometer) mm	Diameter (AHP) mm	Linear wear (roundness) µm	Linear wear (AHP) µm	Volume loss (gravimetric) mm^3	Volume loss (AHP) mm^3
1	1′53–2′07	41.8484 (0.0024)	41.849089 (0.00083)	10.3 (0.3)	10.7 (0.3)	0.313 (0.006)	0.280 (0.022)
2	1′51–2′06	41.8499 (0.0019)	41.850737 (0.00251)	23.3 (0.4)	22.9 (0.3)	0.600 (0.004)	0.575 (0.016)
3	1′52–2′06	41.8477 (0.0013)	41.849245 (0.00193)	2.0 (0.1)	2.6 (0.1)	0.069 (0.004)	0.047 (0.005)
4	1′51–2′07	41.8478 (0.0013)	41.847964 (0.00036)	9.3 (0.2)	11.0 (0.1)	0.306 (0.005)	0.293 (0.001)
5	1′52–2′07	41.8518 (0.0023)	41.852021 (0.00153)	11.7 (0.3)	12.2 (0.2)	0.404 (0.002)	0.392 (0.012)
6	1′53–2′07	41.8453 (0.0023)	41.846755 (0.00144)	3.6 (0.1)	3.9 (0.2)	0.067 (0.006)	0.064 (0.003)

RedLux method is one of one of the high performing methods providing reliable data of the whole surface. The method has a wide range of applications; however, the time efficiency remains a limiting factor. The RedLux method could be also interesting for analysis of polyethylene liners, though in case of more extensive surface damages, polyethylene liner might diverge from the spherical shape what may complicate the RedLux measurements.

Collecting clinical data on retrieved implants from high numbers of patients requires a simple and accurate method. At the same time soft material implants can suffer more extensive wear damages making it difficult for some methods to measure the wear accurately. Both issues were addressed by Yun et al. [18] who used the optical scanning method for analysis of retrieved polyethylene cups. The authors introduced a novel approach to volumetric measurement. Though the study does not describe each step of the analysis in detail, it gives a decent overview of the basic measuring principles. Measurements were performed on 17 polyethylene liners collected from 16 patients during revision surgeries. The samples were scanned using a triangulation 3D scanner (Rexcan III; Solutionix, Seoul, South Korea). The three-dimensional technique involved using two cameras to capture the object under the white light. The mean scan time was 30 minutes (ranging from 25-34 minutes), showing time efficiency of the 3D scanning method. An image processing software (Geomagic, Morrisville, NC) was used to generate the 3D reconstruction images. Wear volume for each of the retrieved liners was measured by subtracting the interior volume of a new liner from the interior volume of a retrieved liner of the same size. The results were compared with the Dorr method of radiographic analysis [19]. Digitalized images of prerevision non-weight bearing hip anteroposterior radiographs were acquired. Radiographs were exported into PowerPoint (2007 Version; Microsoft, Redmond, Wash).

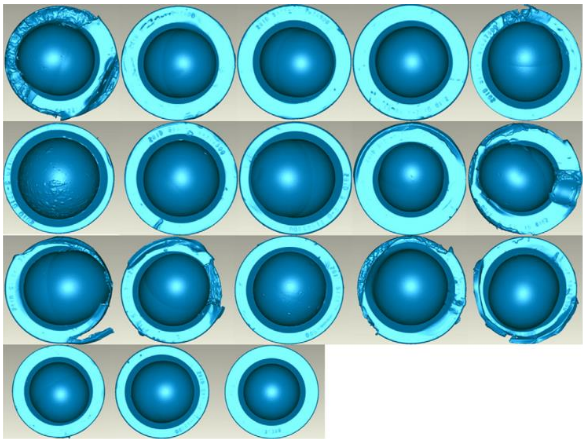


Fig 2.5 Three-dimensional reconstructed images of 17 retrieved PE liner [18]

The mean interior volumes of the 17 retrieved PE liners measured by 2 sets of 3D laser scans were 9172.19 ± 574.70mm^3 (range, 8344.88-10480.71mm^3). The mean interior volumes of the 7 unused PE liners measured by 2 sets of 3D laser scans were 8016.23 ± 0.13 mm^3 .

Study results showed that wear volumes determined by the PowerPoint method strongly correlate with wear volumes determined by the 3D laser scan. The 3D laser scan methodology provides a basic framework for using the optical scanning to determine volumetric wear. For further application of the optical scanning method, it is necessary to provide validation of the method and analysis of the unworn parts of the retrieved liner. The unworn parts analysis is key for determining the original geometry of the liners. Many approaches use new liners with corresponding dimensions as a reference geometry, neglecting the manufacturing error or manufacturing tolerances. Another challenge of volumetric wear determination is the distinction between plastic deformation and material loosening. Finding a border line between these two is difficult, especially with the unknown original geometry and original weight of the liner.

1.1.3 Factors influencing wear analysis

Current methods used for wear analysis enable wear investigations in wide spectra of failures cases. There are several factors that can influence the analysis results. Each of the methods has various limitations as described in the literature review above. To select the most suitable method for analysis, factors such as range of wear, type of implant and type of failure need to be considered carefully.

1.1.3.1 Polyethylene creep

Plastic deformation (creep) is an important factor influencing quantification of the polyethylene wear. The difficulty lies in distinguishing wear in which the PE material is lost from the plastic deformation in which the polymer is distorted in shape but without significant loss of material. Polyethylene is a material with mechanical properties that are time dependent. When a constant load (not higher than the yield stress) is applied, polyethylene deformation increases with time. This process is known as creep. Many studies fail to differentiate material wear from plastic deformations. The authors often do not specify the amounts of creep and wear exactly and both processes are being simply referred to as wear. This is especially true for older studies where this simplification was usually clearly articulated. Puloski et al. [20] went on to state that ‘‘*although the use of the term wear to describe all forms of surface and subsurface deformation may be semantically imprecise, we will continue to use it in this study, acknowledging that the damage can occur without the subsequent generation of debris*.’’ The same approach was taken by Sychterz et al. [21]. This basic approach to wear identification is sufficient for clinical purposes. However, for a better overall understanding of wear, it is necessary to distinguish these two wear mechanisms. Relatively few studies and publications do so, and their results provide us only with basic insights into the problem.

One of the studies in this field published by Lee et al [22] observed creep deformations of UHMWPE over time. The samples were loaded with a constant static strain. Creep processes were observed during loading with subsequent relaxation of the materials. One of the significant studies performed by Bevill et al. [23] on creep and wear predictions shows that while 40% of all wear happens in the first two years of an implants life, 56% of all linear penetration happens in the first 3 or 4 months of this period.

A follow up study on creep published by Penmetsa et al. [24] used the finite elements method (FEM) to simulate wear and plastic deformations of cups. The calculated creep strains were modelled as inelastic. The model was applied to a mathematical model of wear simulations. Results showed the same direction of plastic deformations and head penetration. Creep occurred quickly upon loading with approximately 85% of the total creep penetration occurring within the first 150,000 cycles. Maximum creep penetrations calculated from the full creep analyses ranged from 0.032 to 0.055 mm depending on geometry (Fig 2.6).

Creep poses two major challenges for wear analysis: (1) it leads to distortion of wear rate determined by a selected measuring method and (2) creep changes the contact areas between the articulating surfaces of implant components. Larger contact areas decrease contact pressure what can influence determination of wear scare and a correct identification of the unworn and worn areas of the articulating surfaces.

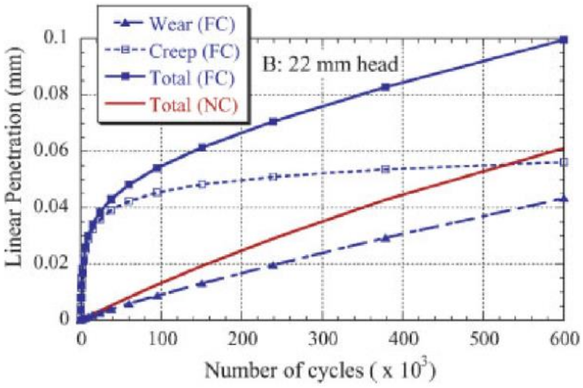


Fig 2.6 Creep and wear penetration levels using full creep properties (FC) and no creep (NC).

The study provided a useful tool for predicting total creep and its development. However, its numerical model implied several simplifications. One of the main limitations is exclusion of the lubrication parameter. The authors also used non-stop hip joint loading, what does not exactly correspond with the human joint environment.

1.1.3.2 Surface analysis

Volumetric wear analysis needs to be complemented with a surface analysis of failed implants for a complex wear analysis. In total hip replacements, where the articulating geometries consist of conforming spherical surfaces, the wear mechanism occurring at a microscopic scale (µm or less) has been associated with polyethylene resistance to multidirectional stress. The multidirectional stress depends on kinematic conditions, load and material of the implants and causes various types surface damages that can indicate various types of wear. Identification of the unworn areas is another important aspect of the surface analysis. The unworn part of the articulating surface is the remaining area of the liner that can provide information on the original geometry of the liner. A correct identification of the unworn area provides important data for reconstruction of the original shape of the liner. The more accurate the reconstruction of the original geometry is, the more accurate is determination of the volumetric wear.

A study provided by Edidin et al. [25] showed basic type of surface damage called multidirectional scratching, including abrasive/adhesive wear mechanism, micro-contact fatigue such as micro-pitting and delamination. Authors focused on the influence of clinical factors on the surface morphology. Surfaces of nine extracted samples of the same size and material were analysed by optical profilometry using the white light interferometry. Surface roughness ranged from 0.142 to 1.7 μm for seven samples that showed multidirectional scratching. Surface roughness for fatigue type of wear showed higher values.

Kurtz et al. [26] studied the initial phase of wear of 21 retrieved implants with short lifecycle using white light interferometry. The unworn surface areas of the liner were recognized by scoring caused by manufacturing machines. Trommer et al. [27] made a similar observation when analysing surface of UHNWPE liners in in vitro conditions. The authors observed interesting scratches caused by third bodies – being either residuals of bone cement used to fix the metal back of the cup or the released material expelled from the contact area between the two surfaces. The authors also observed existence of areas on stainless steel/CoCr femoral heads with apparent material deposition and cracks suggesting brittle behaviour of the deposited material, which may cause appearance of the abrasive third body particles.The calculated linear wear rates were 0.16 mm/year. Three different topographies and morphologies were observed in the region associated with wear: (Fig 2.7 c, d) showed the unworn surface with the machining marks, (Fig 2.7 b) smooth surface with ripple-like morphology resulting from adhesion/fatigue mechanism and cyclic plastic strain accumulation and finally (Fig 2.7 a) showed scratched regions resulting from ploughing mechanism by protuberances of the hard-counter face, with transverse cracks to the ploughing direction.

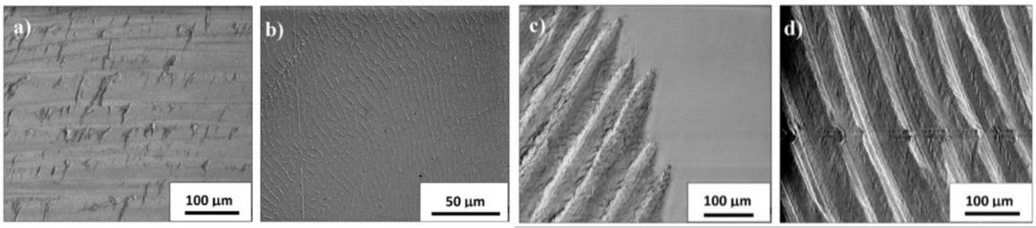


Fig 2.7 SEM images of a UHMWPE cup showing: (a) scratch with transversal cracks; (b) ripples in the polished zones; (c) rough surface with remaining machining marks; (d) unworn surface [27]

1.1.3.3 Factor influencing wear rate

Spatial orientation of the acetabular cup in a patient's body is determined by anteversion and abduction angles. There are surgically recommended intervals for both of these angles, being 20 degrees for anteversion and 40 degrees for abduction according the study published by Scheerlinck et al. [28]. Altering the abduction angle significantly affects the properties of the contact area. Increasing the abduction angle shifts the contact pressure area closer towards the acetabular rim and at the same time decreases its overall size and increases its maximal contact pressure as described by Hua et al. [29].

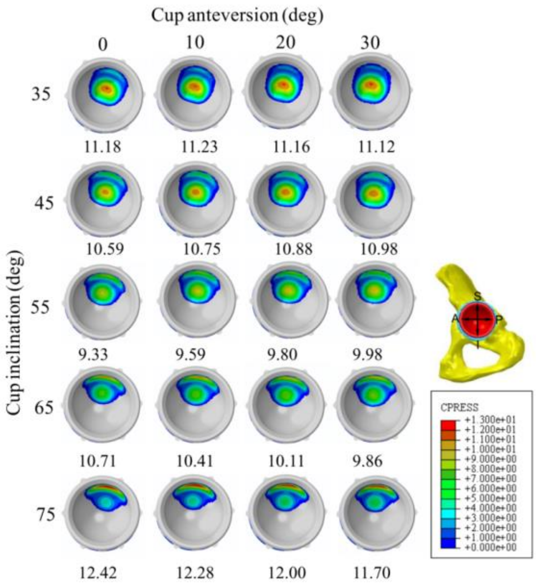


Fig 2.8 Influence of cup inclination on contact pressure

While influence of the acetabular orientation on the contact stress is well documented, a direct relationship between the contact pressure (Fig 2.8) properties and wear mechanism is not fully understood yet. Older studies found no significant correlation between higher contact stress, wear rate and higher abduction angles as suggested by Patil et al. [30]. Some more recent studies such as Halma et al. [31] or Korduba et al. [32] showed decreasing wear rates with increased abduction angles.

Generally higher wear rates are measured when using the radiography compared to simulator wear tests as observed by Kang et al. [33]. These rather significant differences between numerous studies can be caused by multiple factors. For example, simulator studies with strictly controlled conditions do not consider loose third body particles of bone void fillers or bone cement.

3 SUMMARY AND CONCLUSION OF STATE OF THE ART

Better understanding of wear mechanisms is one of the main goals of biotribology and wear of articulating surfaces has been historically the focus of biotribological studies. With better observation technologies and improved implants, more studies started to focus on lubrication and behaviour of implants in human body using clinical data, laboratory simulations and mathematical simulations. However, the material loosening analysis, as one of the key parameters in the process, remains an important research topic. The literature review shows that we still need a better understanding of the articulating surfaces behaviour. With constant enhancements of the implant materials, it is equally important to advance the methods for observation of their interactions.

Several different methods have been developed to determine wear in vitro or in vivo. Radiographic method has been one of the first methods of linear wear analysis. The method is still quite common. X-ray is a routine procedure conducted before and after the revision surgeries for a follow-up examinations and observation of the lifecycle of the implants. Several researchers used software recognition of radiographs identifying edges of implants to determine the linear wear with a better accuracy [2-4, 34, 35]. However, the accuracy was not higher than 2.5 mm. Radiographic methods are not suitable for in vitro testing and there has been an increasing demand for more precise methods providing complex information on wear, including parameters such as direction of wear (wear scare) and surface recognition. The coordinate measuring method has been developed for investigation of artificial wear using wear simulator. The method was initially designed as a contact method [12, 13] with the pointing stylus defining coordinates in different points of the articulating surface of implants. This approach has several limitations as well. One of them is point spacing that causes polygonization error [36] during post-processing. Another issue is geometry distortion caused by neglecting the plastic deformation of the implant.

Nevertheless, the coordinate measuring method remains one of most important methods for in vitro testing. Coordinate measuring method procedures and their usage for hip joints implants are described in Standard ISO 14242, Part 2 [11]. The method has been modified by replacing the touching stylus with an optical sensor. One of the well-known modifications of the coordinate measuring method is the RedLux method [17]. Majority of authors using the RedLux method focus on hard materials such as metal and ceramics. Polyethylene liners have not been investigated much using this method.

Various factors influencing wear rate are often mentioned in context of wear analysis methods. We focused on methods enabling 3D surface analysis and wear determination, where creep is one of the major factors contributing to distortion of the wear analysis. Range of the creep deformations depends on positioning of the acetabular cup and on wear modes involved. Reviewed studies showed that major development of creep deformation occurs in the run-in phase of the implant. Representation of the creep strains was inelastic. In vitro simulation experiments involved continuous loading that allowed a more limited creep recovery than in vivo loading. Simulations showed that around 85% of the creep occurs in first 150 000 load cycles [22]. Authors argued that the creep of polyethylene liners quickly changed the head–liner contact mechanics and increased an early head–liner penetration what could distort wear analysis based on surface investigation. Though, according to the authors, the creep properties of the liner did not affect volumetric wear. There are relatively few studies investigating the creep process.

The final part of the literature review studies effects of liner position in human body on the material loosening. Various investigations on relationship between the wear progress and inclination angle of liners showed different results. Earlier publications documented influence of cup positioning using radiographic records. These - mostly clinical - studies recommended abduction angle of 40 degrees and anteversion angle of 20 degrees to avoid complications. However, some patients with anatomic variations or with afunctional pelvic orientation outside the normal range would require a customized cup position. [28]

Finite elements analysis proved influence of the abduction angle, which significantly changes the contact pressure on the liner surface influencing the volume of material loosening [29]. More recent studies describe relationship between the abduction angle and volumetric wear. Tests examining the conventional UHMWPE samples using the gravimetric method found decreasing volumetric wear with an increasing abduction angle [32]. The authors explained this phenomenon by smaller contact area for abduction angles above 55 degrees. On the other hand, higher abduction angles showed higher risk of the edge load effect. Though the edge load effect does not influence the volumetric wear significantly, it entails higher risk of liner fracture and luxation.

The literature review shows that measurement methods that are currently used for wear analysis are not suitable for analysis of retrieved polyethylene liners. It is necessary to seek new approaches. Optical methods seem to offer a promising direction in this respect – providing advantages such as time efficiency, large number of measuring points and the possibility of a complete geometry reconstruction. However, the accuracy of the methods remains questionable and has not been investigated yet. Developing a new approach opens new ways to obtain information on retrieved implants which are a good source of material for investigation of the relationship between the material loosening and position of the liner and for a better understanding of the wear mechanisms in general.

4 AIM OF THE THESIS

The aim of this doctoral thesis is to establish a new approach to volumetric wear assessment for acetabular polyethylene liners using optical methods. The aim is to develop and validate an optical method that is suitable for wear analysis of polyethylene liners. Surface topography and mechanical properties of the polyethylene liners will be explored to describe the changes of the articulating surface of the retrieved implants and to expand the wear analysis of the implants. To achieve the main goal of this thesis, following steps were taken:

- Development of a volumetric wear assessment method for retrieved polyethylene implants using an optical scanner.
- Validation of the method according to the ISO 14242 Standard.
- Demonstration of usability of method on liners retrieved during the revision surgeries
- Surface topography analysis of the samples.
- In- vitro tests to observe the run-in phase of the samples under various inclination angles.
- Data analysis.
- Conclusions and discussion of the results.

1.1 SCIENTIFIC QUESTIONS

Q1 How can the accuracy of the optical scanning method and errors during data post-processing influence wear determination of retrieved polyethylene liners?

Q2 What is the influence of wear rate on mechanical properties and surface structures of polyethylene liners?

Q3 What is the influence of liner position on plastic deformation of the liner?

1.2 HYPOTHESES

H1: The optical method will be able to approximate the original surface geometry with a better accuracy than current methods that use new lines for approximation of the original geometry and hence will be more accurate in determining the wear – in correlation with the gravimetric measurements.

H2: Retrieved polyethylene liners that survived longer time in situ will show lower rate of material loss per year with no extensive changes of their surface structures.

H3: Retrieved liners with lower abduction angle will have lower wear rate and lower plastic deformations due to decreasing contact pressure in the articulating area.

1.3 THESIS LAYOUT

This doctoral thesis is composed of three papers published in journals with impact factor (Paper A, B, C). The main aim of this thesis is to develop a new approach to optical measurements and to prove usability of this method for volumetric wear determination. Paper A introduces the new method. Optical scanner was used to gather surface data for both new and worn polyethylene liners. The paper describes liner geometry reconstruction and creation of 3D models for volumetric wear determination. The new method was validated by a standard gravimetric method that is usually used for this purpose. Finally, the new method was applied to determine volumetric wear of 13 UHMWPE liners retrieved during revision surgeries. Results of the volumetric wear analysis were compared with clinical data. As the optical scanning method can analyse the samples down to the micrometer scale, we supplemented the optical method with a surface analysis to examine a more detailed microscopic structure of failed liners. The surface analysis was carried out using a profilometer with a positioning stage allowing determination of topography areas. The resulting microstructure of the surface showed extensive mechanic damages that were further examined using chemical and mechanical analysis and then summarized in Paper B. The measurements were performed in cooperation with the University of Arkansas in the USA. The final part of this doctoral thesis, Paper C, focuses on the relationship between liner position, plastic deformations and volumetric wear of the liner.

A. RANUŠA, M., J.GALLO, M.VRBKA, M.HOBZA, D.PALOUŠEK, I.KŘUPKA and M. HARTL. Wear Analysis of Extracted Polyethylene Acetabular Cups Using a 3D Optical Scanner. *Tribology Transaction*, 2017, 60(3), 437–447.

B. CHOUDHURY, D., M.RANUŠA, R.A.FLEMING, M.VRBKA, I.KŘUPKA, M.G.TEETER, J.GOSS and M. ZOU. Mechanical wear and oxidative degradation analysis of retrieved ultra high molecular weight polyethylene acetabular cups. *Journal of the Mechanical Behavior of Biomedical Materials*, 2018, 79, 314-323.

C. ZEMAN, J., M.RANUŠA, M.VRBKA, J.GALLO, I.KŘUPKA and M. HARTL. UHMWPE Acetabular Cup Creep Deformation during the Run-in Phase of THA's Life Cycle. *Journal of the Mechanical Behavior of Biomedical Materials*, 2018, In Press.

5 MATERIALS AND METHODS

5.1 EXPERIMENTAL DEVICES

Several different devices were used for the wear analysis in this thesis. An optical scanner ATOS Triple Scan was used to develop the novel measurement method. An optical profiler was used to analyse the surface topography, Raman spectrometer was used for chemical analysis and a nanoindenter for mechanical analysis of the surface. A customized hip joint simulator was used to investigate various inclination angles and plastic deformations of polyethylene liners.

5.1.1 Optical scanner

Acetabular cups were measured using the 3D optical scanner ATOS Triple Scan (GOM,GmbH). The optical system is based on an active fringe projection and triangulation. The ATOS Triple Scan uses the "Blue Light Technology" in three viewing angles between a stereo camera and a projector. Thanks to this approach, the measurements are not dependent on environmental factors and therefore it is not necessary to maintain constant environmental conditions during the measurements. Final scan is comprised of several partial scans that are aligned according to software-detected reference points.

5.1.2 3D optical profiler

The initial surface topography of all tested samples was analysed in a greater detail using a 3D optical profiler contour GT-X8 (Bruker, USA). The measurements were based on the phase shifting interferometry technique. The range of the vertical axis is down to 0.1 nm which is completely sufficient for the purposes of this thesis, since the surface roughness of the tested femoral heads and acetabular liners is in the range of units of µm or higher. The commercial machine was customized by installing a rotational stage allowing to position the samples in a polar coordinate system.

5.1.3 Raman analysis and nanoindentation

Confocal Raman microscope (inVia™, Renishaw) was used to observe microstructures of the retrieved UHMWPE liners, particularly variations in the orthorhombic crystalline phase fraction and oxidation indices. Measurements were carried out in cooperation with the University of Arkansas, USA. The excitation source had a 785 nm wavelength, yielding a power of approximately 1.5 W, with an exposing time of 30 seconds and a spot size of ~100 µm in diameter. The generated Raman spectra (800-2000 cm-1) were processed in the Origin software and the integrated peaks were measured around 1293, 1305, and 1414 cm-1 The hardness and modulus of elasticity were measured using an instrumented nanoindenter (TriboIndenter, Hysitron Inc. Minneapolis, MN) with a diamond Berkovich tip having a 100 nm tip radius. Normal loads of 500 µN were chosen for the nanoindentation with 5 indentation tests under the same test conditions that were used for the Raman spectroscopy.

5.1.4 Wear simulator for hip joint testing

Hip simulator was used to subject hip implants to physiological loading and motions. We used a customized, fully servo-driven hip simulator featuring uniaxial load and two motion axes. The physiological load was applied through spring compression using twin peak 3000 N load gait cycle with 1 Hz frequency according to the ISO 14242-1. (**Chyba! Nenalezen zdroj odkazů.**) displays a scheme and basic measurement principles of the simulator. Orientation of the two motion axes relative to the load line was chosen to simulate the flexion/extension (applied on the femoral head, range -18° / +25°) and the inner/outer rotation (applied on the acetabular cup, range -10° / +2°) motions. Lack of the third abduction/adduction motion axis as specified in ISO 14242-1 was compensated by a phase shift of the flexion/extension and inner/outer sinusoidal motion curves by 90° according to ISO 14242-1 (Fig 5.1). A sleeve sealing on the heating platform of the simulator is necessary for fully flooded contact pairs. Platform can be heated up to a tested temperature using heating patrons.

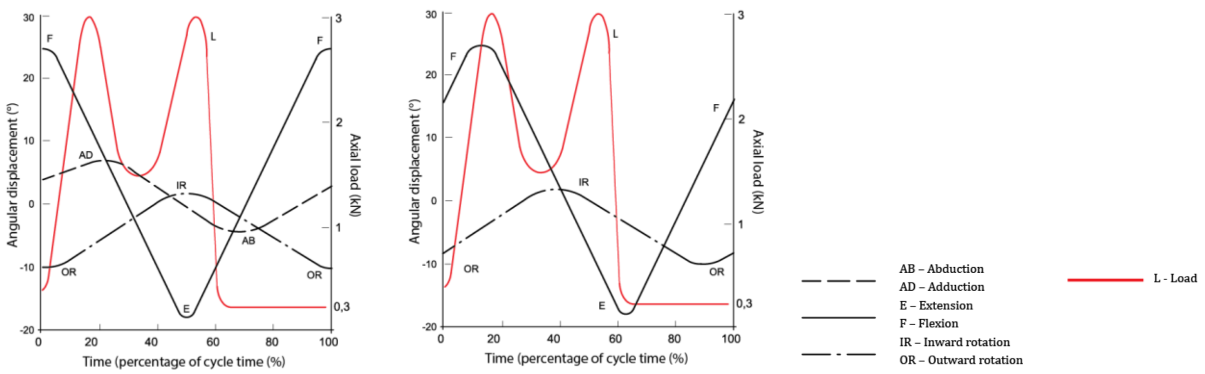


Fig 5.1 Phase shifting cycle of kinematic conditions

5.2 EXPERIMENTAL DESIGN

5.2.1 3D geometry analysis

Scanned data were post-processed using the software GOM Inspect (GOM mbH). First, the scan was polygonised and smoothed with surface tolerance of 3 µm to remove the surface roughness and possible coating defects that could distort the measurements. The process can be described in following steps:

- **Removing of damages** caused by surgeon. In some cases, surgeon caused more extensive damages to polyethylene liners during the revision surgery, what could complicate further analysis. However, thanks to large number of scanned points it was possible to reconstruct the damaged areas.
- **A reference coordinate system** for liner geometry was created using three fitting elements: a line, a point and a plane. The line represented a direction of the wear path (also described as a wear scar) and was used to identify the unworn parts of the samples. The direction of the wear scar was obtained by an initial comparison of the scanned data with nominal data of a new acetabular cup using the best fit function of GOM Inspect. This comparison rendered a map of deviations that enabled us to infer the final direction of the wear scar. The point was defined by the centre of a sphere with a diameter corresponding to the original dimensions of the acetabular cup defined by the unworn part of cup. The plane was defined by the rim of the acetabular cup.
- **Wear vector determination**. Polygonal data with the defined coordinate system were then used to determine the wear vector as a vector originating from the centre of the unworn cup geometry to the most worn point on the inner surface of the cup.
- **Reconstruction of the original geometry.** A 3D model of the articulating surfaces of the original geometry was created using the unworn parts of the liner.
- **Surface and volume creation.** Polygonal data were exported to a STL format for further post-processing with the Geomagic Design X (3D Systems GmbH) software. Quality of this transformation was evaluated by comparing the rendered surface model with the polygonal data. We found that the uncertainty was under 2 μm. Volumetric model of the retrieved samples was created after a complete reconstruction of the surface geometry.
- **Wear determination.** Volumetric wear of the samples was determined by comparing the volumetric model of retrieved samples with their reconstructed original geometry.

5.2.2 Surface analysis

A 3D optical microscope ContourGT-X (Bruker, USA) was used to analyse the surface topography of 13 retrieved cups with various extent of wear. Topography measurements were evenly distributed around the articulating surface with 79 points. Each measurement position was defined by polar coordinates and compared with the wear distribution obtained by the optical scanning method. Ra value was evaluated as an arithmetic average value a of filtered roughness profile determined by deviations from the centre line. The roughness values were sorted according their frequency and compared with the individual categories of wear mechanism.

5.3 EXPERIMENTAL CONDITIONS

5.3.1 Validation of the 3D scanning method

The 3D optical scanning method was validated by a gravimetric comparison according to ISO 14242 using analytic balances Kern ABS 320-4N with resolution of ±0.1 mg. The wear of the extracted cups was simulated simply by removing the material from new cups. The wear was simulated on a hip pendulum composed of two main parts: a base frame with acetabular cup and a pendulum with femoral head. The pendulum oscillated freely in the flexion-extension plane. The pendulum set-up is described in details elsewhere [37]. The material loss of new cups was measured in six simulated wear cycles, each cycle lasted 15 minutes and the process was replicated on three cups. As the surface damage was not intended for validation investigations, femoral head was damaged extensively to increase the wear and to decrease the time of experiment. The amount of removed material was within the range corresponding to the average natural material loss in human body for similar type of implants (21 – 74 mm^3) as showed by radiographs of the patients [38].

5.3.2 Experimental conditions for creep test

The creep experiments were conducted using a custom hip joint simulator as described above. Three physiological orientations with different abduction angles were tested. Abductions of 30°, 45° and 60° were chosen to represent the whole surgically recommended abduction interval. Anteversion angle remained unchanged at 15 degrees (approximately in the middle of the recommended interval) for all three cases to isolate the influence of abduction. The hip replacement components were submerged in pseudo-synovial fluid during simulator testing. The fluid was based on phosphate-buffered saline serum with addition of Albumin (28 mg/ml) and γ-globulin (9.4 mg/ml) proteins. The whole containment with the flooded hip articulating components was heated to 37 °C with accuracy of ± 2 °C according to the ISO 14242-1 using heating elements in the containment's bed.

The simulator ran for total of 50 000 gait cycles with series of measurements starting in the initial brand-new state of the implants and then repeated after every 10 000 gait cycles to observe development of liner deformations in the run-in phase. Results of the experiment were published in the article C.

6 RESULTS AND DISCUSSION

We have introduced a new optical scanning approach to measurements of the polyethylene hip joint acetabular liners wear. Thanks to their time efficiency and accuracy, optical scanning methods are used widely across many industries. Application of the method for wear analysis required two steps: first the liners were conventionally scanned and then the scanned data were post-processed accordingly to yield inputs for the wear analysis.

The method was demonstrated on thirteen retrieved polyethylene liners and validated on three new liners according to the ISO 14 242 Standard defining standard testing requirements based on kinematic of human gait for other wear measurement methods such as gravimetric method and coordinate measuring method. In case of the retrieved liners, the post processing and further analysis were complicated by the unknown original geometry of the samples. However, it was still possible to reconstruct the original geometry using the unworn areas with negligible damages of the retrieved liners. The unworn areas could be identified by scoring from manufacturing machines. Design of the new wear analysis approach including measurements, data post-processing, demonstration on retrieved liners and validation on new liners is described in paper A. High number of collected points (191 500 surface points) ensured high quality of surface transformations with deviations less than 0.002 mm.

Despite the high-quality surface data, the problem of cold flow phenomenon, called also creep or plastic deformation, remained. Plastic deformation without release of actual wear can cause distortions in volumetric wear analysis, especially when using methods other than gravimetry.

The problem of creep was partially eliminated during the validation phase, when the extensive damages of the head allowed material loosening from the beginning of the whole process, while the material could relax in between the measurements.

During the validation phase, material loss of new cups was measured in six simulated wear cycles using both the gravimetric and 3D optical methods. Each cycle lasted 15 min and the process was replicated on three cups. Validation was performed by gravimetric method according to the ISO 14 242 Standard as mentioned above. Results of the validation showed deviation of 0.0040 g, 0.0021 g and 0.0029 g, corresponding with 2.2 – 4.3 mm3 of material loss. Repeatability of the optical scanning method was evaluated on the inner diameter of a new cup. Ten various measurements showed deviation of 0.005 mm.

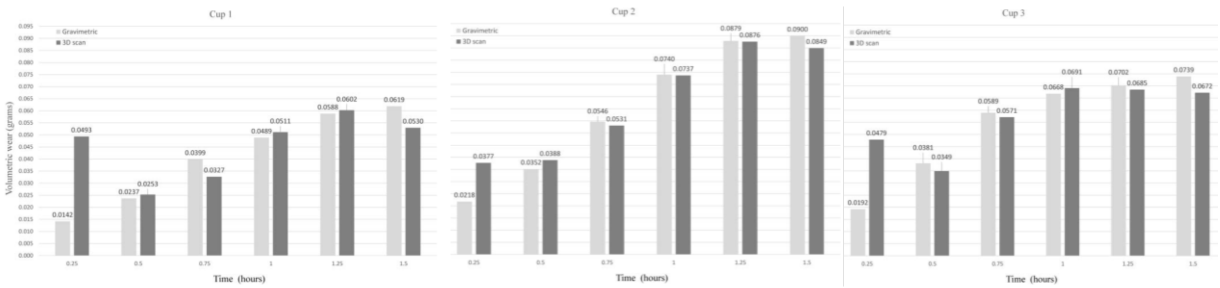


Fig 6.1 Comparison of validation test results of 3D scan and gravimetric method

From the accuracy perspective, coordinate measuring method or RedLux method proved to be more accurate than the optical scanning method [17]. However, they have limited use for analysis of liners showing more extensive damages. Due to its lower precision, the optical scanning method is not suitable for analysis of hard components. On the other side, the accuracy of optical scanning method is fully acceptable when it comes to the analysis of polyethylene components, especially those with extensive damages. The ability to measure the whole geometry of a liner, including its rim and any possible extensive damages is one of the main advantages of the optical scanning method. Number of collected points is also significantly higher compared to other methods. This is important especially for reconstructions of damages caused by surgeon during extraction that, when left unnoticed, may distort the volumetric wear determination. High number of collected points enables to replace the surgeon damage with a new surface during post processing, while the curvature is calculated based on the surrounding elements.

As the surface structure is one of the parameters influencing correct volumetric wear determination, we conducted a surface analysis of 13 retrieved UHMWPE Bicon-plus implants (Smith and Nephew, Switzerland). The Bicon- plus implants are still relevant in clinical practice in the Czech Rebublic, even though being increasingly replaced by newer generations of implants. The 13 liners were extracted during revision surgeries. Liners were scanned by an optical scanner to determine the wear rate. Then we analysed surface roughness with Contour GT-X8 profiler using the principle of phase shifting interferometry. Wear scare of the articulating surface was determined according to the wear vector and angle of penetration and surface roughness was then compared with the clinical results.

The average linear wear was 0.13 mm/year (ranging from 0.06 to 0.3 mm/year), and the mean value of total volumetric material loss was 44.37 mm3/year (ranging from 9.98 to 125.85 mm3/year). Using the optical profilometer, a map of roughness distribution of the individual cups was created. For each implant, 76 values of roughness were measured, and each measurement was evaluated on an area of 0,22mm2. Based on their roughness and topography, liner surfaces were then sorted into several different categories of wear mechanisms: surface polishing, abrasive-adhesive wear, surfaces with preserved grooving, surfaces with substantial plastic deformation and delamination. The abrasive-adhesive surface wear was between 0.1

– 0.3 µm and was observed mostly in patients without loosened implant components.

The abrasive wear was defined by typical and significant scratches corresponding with direction of the wear scare. Character of scratches suggested presence of third body particles in the contact areas. The adhesive wear was distinguished by polished surface and decreased roughness compared to the original surface that was preserved in the unworn parts of the liner. The abrasive wear was accompanied with pitting – a process assigned to fatigue of polyethylene. This effect was observed in patients with longer lifespan of implants, on average 10,5 year (SD 2,5 year). Damages such as cracks, significant plastic deformation or delamination were also observed in implants with a longer lifespan. Extensive surface damages could have been caused by changing material properties and chemical degradation of the surface. As expected, extensive damages of liners correlated also with higher linear wear and – except for the extreme causes such as implant fractures – also with a higher abduction angle in pelvis. Linear wear rate exceeding 0.1 mm/year correlates with an increased risk of osteolysis formation as mentioned in several studies [39-41]. The examined implants resisted osteolysis even though the above-mentioned conditions were met. Though the number of samples was not statistically significant to make valid conclusions, the results may serve as hypotheses for future research.

Paper B focused on mechanical and chemical degradation of ten extracted polyethylene Bicon-plus liners with the same specifications as the 13 liners studied in paper A. The 10 samples were extracted during revision surgeries between 2015 and 2016 and their survival time in vivo was on average 9.52 years (range: 0.1–16.76 years, SD 4.69 year). Measurements and analyses were carried out in cooperation with the University of Arkansas in the USA due to availability of measurement devices and knowledge in this field.

All 10 samples were divided into three groups according to the reason of revision: (1) aseptic loosening and extensive wear, (2) pain and (3) other reasons such as a dislocation, articular ossification and osteolysis. Surface deviation measurements were carried out for each liner to determine the linear wear and deviation map. Positive values on the deviation map indicated material inflation and negative values indicated wear and creep. Direction of penetration was relative to the axis of liner and was defined by the wear vector. Samples 1–3 from the group 1 had smaller wear vector angle, 16 degrees on average, and corresponded with the lowest rate of linear wear, on average 0.09 mm/year.

Samples in groups 2 and 3 had obviously higher wear vector angles of around 73.7 degrees and likewise showed increasing linear wear of 0.45mm/year. Changes in wear rate could indicate changes in the material behaviour of the surface. All liners were analysed using Raman spectroscopy. Oxidation indices showed a clear sign of chemical degradation in the retrieved prostheses, and these mostly correlated with wear depth. Oxidation index and volume fraction of orthorhombic phase are very significant, since both are closely related to the oxidative degradation of tribo-corrosion process. Hardening and stiffening were also identified in the liners. Samples representing each type of failure were chosen for hardness and modulus of elasticity measurements using nanoindentation on the surface of the samples (indentation depth is below 2 µm). All the measured samples showed an increased hardness and stiffens range compared to new samples. Several studies showed that the hardness and elastic modulus is a key material property that is related to tribological performance [42]. The advantage of the above-mentioned approach is the possibility to match measurements of hardness and stiffens with the map of surface deviations. Thanks to wear scare and angle of head penetration, position of the retrieved liner in human body can be identified in reverse.

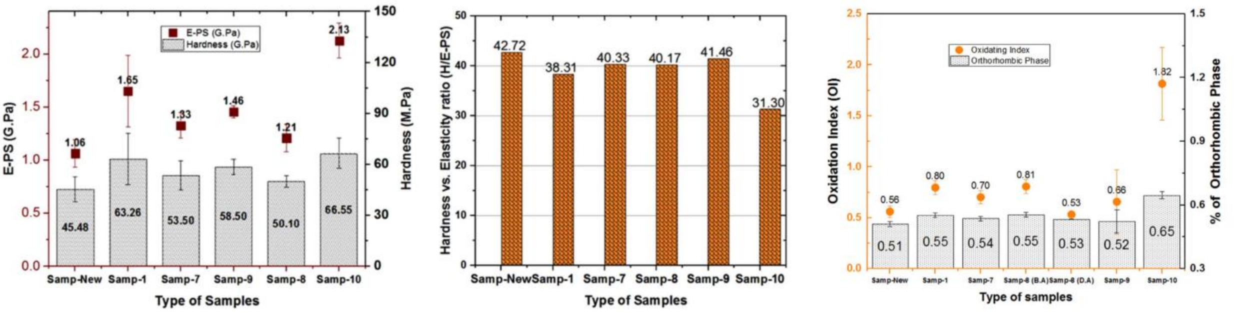


Fig 6.2 Mechanical properties of selected samples: (a) hardness (H) and modulus of elasticty (E), and (b) ratio of hadness Vs. Ealsticty (H/E-PS), oxidation index

Results outlined in paper B indicated a possible relationship between the wear rate, creep and position of the acetabular cup in pelvis. The literature review showed influence of the abduction angle on load distribution and hence on wear and creep. Confirmation of this relationship can influence both the wear rate of the implants and quantification of wear using optical scanning methods. Therefore, we continued to study the liner position in the run-in phase of its lifecycle.

Paper C investigated three new samples tested on a hip simulator to study creep deformations and influence of the abduction angle. We investigated several angles of acetabular abduction that are frequently used in the clinical practice. Three main deformation regions of the cups' bearing surface were distinguished. The first deformation region was the region affected directly by head's penetration with most profound compression deformations. This oval-shaped region was positioned in the direction of applied force, moving closer to the superior quadrant of the acetabular rim with an increasing inclination angle. However even in case of the liner with the highest tested inclination angle of 60-degrees, this deformation region did not involve the cup's rim itself. The first region of the most profound deformations was surrounded by the second region of shallow compression deformations ranging up to the inferior quadrant of the cup's rim. The third region of plastic deformations was in the posterior-superior quadrant of the acetabular rim. Inflation areas (or plastic deformations) were observed also in liners that were analysed in paper B. Rim deformations cause potential risk of liner cracking in this area as demonstrated by Brazier et. al. [43], and corresponds with the predicted distribution of contact stress as described in an earlier finite elements analysis study [29]. The elevated rim increases radial clearance of the hip replacement with possible consequences for lubrication processes [37]. In addition to the methods described earlier in this thesis, the damaged surfaces of the tested liners were also observed using scanning electron microscopy after the performing of tests. The brand new acetabular cups showed spherical articulating surface with distinctive circular marks from the manufacturing process. These marks were evened out to a smooth finish with the femoral head during the first 10 000 to 20 000 gait cycles. Development of fine multidirectional scratches replacing the initial bearing surface structure was observed at up to 50 000 gait cycles. The maximal depths of compressive creep deformation were between 0.04 – 0.05 mm and are generally on the lower end of those predicted by previous studies. This supports usage of creep model parameters taken over from static creep tests for creep depth measurements [44].

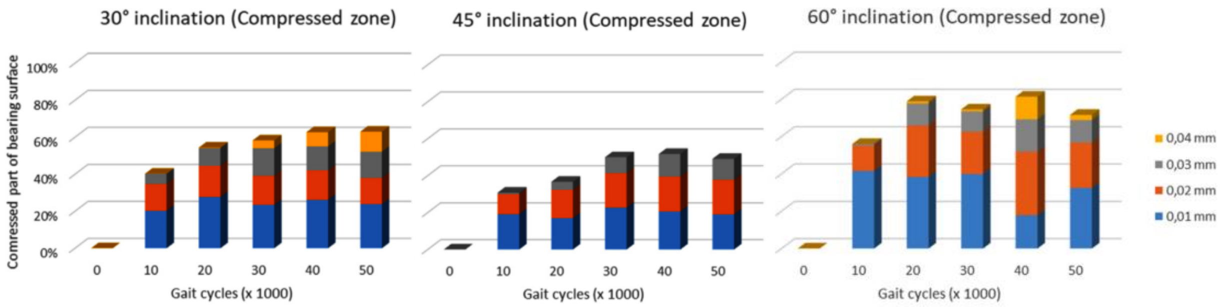


Fig 6.3 Depth of the compressed zone.

The relaxation periods allowed not only to observe just the irreversible plastic creep deformation, but the cyclic applying and relaxing of the elastic strain could also support both the processes of strain-induced recrystallization of UHMWPE and lamellae alignment perpendicularly to the applied load. The increased crystallinity and aligned crystalline phase increase the elastic modulus and hence improve the creep resistance. On the other hand, an increased elastic modulus increases maximal value of the Hertz contact stress, making the acetabular cup prone to fracture and delamination. As for the limitations of this study, we used the conventional polyethylene cups as test samples, while nowadays XLPE acetabular cups are more common. On the other hand, the crosslinking itself does not affect creep mechanism, not nearly as much as the wear resistance does. Moreover, the conventional polyethylene is better comparable with the liners retrieved during the revision surgeries nowadays. This can lead to better understanding of wear mechanism in the human body and the resulting knowledge can be applied for the newest generation of polyethylene cups.

7 CONCLUSIONS

Total hip replacement surgery is a standard treatment of degenerated or damaged hip joints with numbers of primary arthroplasties increasing every year. At the same time, revision surgeries caused by failed implants are increasing too; with wear being the main factor limiting the longevity of the artificial implants. Wear analysis is one of the most important sources of knowledge on the tribological processes. Complicated tribological mechanisms involving interaction of materials, lubrication, structural surface changes and geometry modifications contribute to the wear rate.

The first part of this thesis showed that the coordinate measuring method and its alternation, RedLux method, though suitable for hard materials such as metal-on-metal or ceramics-on-ceramics implants, are limited in their application for polyethylene liners due to a complicated reconstruction of the surface geometries with extensive surface damages.

Article A

The main goal of this thesis was to introduce a new approach to determination of volumetric wear of polyethylene liners using optical scanning methods and to evaluate this new approach in the context of the existing research. We expanded the optical measurements with a surface analysis and with investigations of roughness changes across articulating surface of liners [45].

New approach of volumetric wear investigation by the optical scanning method was developed, validated and demonstrated on 13 samples.We found that positioning of a liner in human body can influence wear rate as well as type of changes in its surface structures. Several higher abduction angles showed impact on stability of the cup and its survival time in situ after the THR. We found that the higher was the abduction angle, the higher was the wear rate, especially for abduction angles above 50 degrees. However, the relationship between the wear rate of retrieved polyethylene liners and their survival time in situ was not clearly linear. This suggests shows the possibility of other factors influencing the wear. Several types of surface structure changes such as delamination, pitting, plastic deformation and abrasive/adhesive type of wear were found across all samples. The study is limited by low number of a single-type liners used for measurements and analysis.

Article B

A new group of retrieved samples showed changing mechanical and chemical properties such as roughness, hardness, elasticity and oxidation index with increasing wear rate. Oxidation index was significantly higher compared to a new sample and values varied across the surface. Modulus of elasticity and hardness on surface were also higher (hardness vs. elasticity ratio was lower) compared to a new polyethylene liner.

Article C

The article C investigated relationship between the acetabular cup positioning in pelvis and development of plastic deformation. Three new liners positioned in three various inclination angles chosen according to surgical requirement were investigated in their run-in phase. Results showed that the initial plastic deformation of liner geometry was strongly influenced by the inclination angle of the liner in pelvis. We found the smallest plastic deformation at the angle of 45 degrees. At higher and lower angles, the plastic deformation increased. The friction coefficient changed during the first 10 000 cycles of the simulated gait and varied with different angles. Flake shaped delamination of the surface and first material loosening followed the plastic deformation.

The main contribution of the thesis can be summarized into the following points:

- New approach of volumetric wear investigation by the optical scanning method was developed and demonstrated.
- Analysis of 23 retrieved liners was performed to identify linear and volumetric wear. The identified wear scare region was analysed by surface analysis. We found four elementary types of wear mechanisms as a delamination, plastic deformation, abrasive/adhesive and scoring occurring together with the remaining unworn areas of the original geometry.
- Mechanical changes and chemical degradation such as plastic deformations, increased oxidation index and decreasing hardness vs elasticity ratio were observed in retrieved liners.
- We confirmed experimentally the results of FEM studies predicting the contact stress distribution in relation to inclination angle. We found the smallest plastic deformations at angles around 45 degrees. At the same time these angles showed significantly larger elevated areas of the rim, with rim being one of the main weak spots, where liner fractures occur frequently.

Regarding the scientific questions and hypotheses, our findings can be summarized in following concluding remarks:

H1: The optical method will be able to approximate the original surface geometry with a better accuracy than current methods that use new lines for approximation of the original geometry and hence will be more accurate in determining the wear – in correlation with the gravimetric measurements.

The optical scanning method was validated using the gravimetric method on new samples. The new samples were worn in 6 cycles and the resulting deviation between the methods was 2.2 – 4.3 mm^3. *This method is less time consuming than the conventionally used CMM method. Another advantage of the method is the ability to develop a complex geometry built on a large number of points. This approach enables us to reconstruct the most accurate original geometry.* ***(Hypothesis H1 was confirmed).***

H2: Retrieved polyethylene liners that survived longer time in situ will show lower rate of material loss per year with no extensive changes of their surface structures.

Relationship between the wear rate of retrieved polyethylene liners and their survival time in situ was not clearly linear. Changes of surface structures such as delamination were found both in samples with higher and lower wear rate. Several samples with abrasive/adhesive type of wear showed higher wear without extensive changes of surface structures. We defined the change of surface structure as extensive in cases when: (1) the surface roughness of the respective area was higher than the surface roughness of the unworn parts of the retrieved lines and (2) the area did not show scoring caused by manufacturing machines. ***(Hypothesis H2 was falsified).***

H3: Retrieved liners with lower abduction angle will have lower wear rate and lower plastic deformations due to decreasing contact pressure in the articulating area.

We tested the hypothesis on new samples during their simulated run-in phase. We found the smallest plastic deformation at the abduction angle of 45 degrees. At higher and lower angles, the plastic deformation increased. ***(Hypothesis H3 was falsified).***

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1. RANUŠA, M., J. GALLO, M. VRBKA, M. HOBZA, D. PALOUŠEK, I. KŘUPKA and M. HARTL. Wear Analysis of Extracted Polyethylene Acetabular Cups Using a 3D Optical Scanner. *Tribology Transaction,* 2017, 60(3), 437–447.

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5. RANUSA, M., J. ZEMAN, M. VRBKA, J. GALLO, I. KŘUPKA and M. HARTL. Effects of Polyethylene Acetabular Liner Orientation on Run-in-Phase Deformation. 4th International Conference on BioTribology, Montreal, Canada.

CURRICULUM VITAE

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Education

- **2014 – 2018** Doctoral study at Institute of Machine and Industrial Design, Faculty of Mechanical Engineering, Brno University of Technology. Topic of the dissertation thesis: *Volumetric wear analysis of hip joint implants by optical methods.*
- **2012 – 2014** Master study at Institute of Machine and Industrial Design, Faculty of Mechanical Engineering, Brno University of Technology. Topic of the diploma thesis: Design of valve block for hydrostatic recuperative module of vehicle.
- **2009 – 2012** Bachelor study at Faculty of Mechanical Engineering, Brno University of Technology. Topic of the bachelor thesis: *Equipment to vehicles energy recovery simulation.*
- **2005 – 2009** Secondary Industrial School, Nové Mesto and Váhom. Branch: Automatization.

Awards

- **2017 -** Rector's Award for Pneumobil Racing Team Brno

Teaching activities – seminars:

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Participations in scientific projects

- 2017 – 2019: Study of the influence of lubricants rheology in elastohydrodynamic lubricated contacts (FSI-S-17-4415).
- 2017: Innovation of subject teaching of tribology through employ of optical digitalization in biotribology. (FV 17-18)
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Internships

- 06/2018 – 12/2018 Rush University, USA
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Language skills

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Scientific activities

- Biotribology - wear of artificial hip joint

ABSTRACT

This dissertation thesis deals with wear analysis of total hip replacements (THR) using optical methods. We introduced a new approach to volumetric wear assessments of polyethylene liners using a 3D optical scanner. The new approach brought benefits of time-efficient measurements, large number of points collected for post-processing, the possibility to create pre-worn models of retrieved samples as well as the possibility to exclude damages caused by surgeon during revision surgeries. The method was validated by gravimetric method according to the ISO 14242 Standard. The new approach was then used in three studies focusing on wear rate and mechanical changes of polyethylene liners. In the studies, the analysis of polyethylene liners geometry was followed by a detailed surface analysis of contact areas down to the microstructural level. Clinical history data for 23 retrieved liners combined with wear analysis showed several issues affecting failure of the polyethylene implants. We worked with Bicon-plus type implants, that are widely used in clinical practice in the Czech Republic. Structural surface analysis of the retrieved samples showed several different wear mechanisms such as adhesion/abrasion, pitting, delamination and plastic deformation. Analysis of material behaviour showed mechanical changes and chemical degradation in retrieved prostheses which mostly correlated with the wear depth. Investigated samples showed plastic deformations, an increased oxidation index and lower hardness to elasticity ratio compared to the new samples. Creep phenomenon or plastic deformation, which was investigated in the final part of thesis, occurred in all the retrieved samples. Further in vitro testing showed presence of creep in the run-in phase of implants.

This thesis aimed to introduce a new approach to wear analysis using the optical scanning method and to apply the new approach for investigations of surface geometry of retrieved polyethylene liners. The method proved to be a suitable method for investigations of retrieved polyethylene liners helping to better understand the processes leading to implant failures.

ABSTRAKT

Predložená dizertačná práca sa zaoberá analýzou opotrebenia totálnych bedrových endoprotéz za použitia optických metód. V práci bol predstavený nový prístup hodnotenia objemového úbytku materiálu pomocou 3D optického skeneru. Tento nový prístup je časovo efektívny, poskytuje veľké množstvo snímaných bodov na povrchu implantátu. Množstvo bodov umožňuje presnejšiu rekonštrukciu pôvodnej geometrie a prípadné rekonštrukcie nežiaducich poškodení polyetylénovej vložky pri extrakcii. Predstavené metóda bola validovaná za pomoci štandardizovanej gravimetrickej metódy v súlade s ISO 14242. Následne bol optická skenovacia metóda použitá v troch štúdiách zameraných na analýzu opotrebenia, mechanické zmeny artikulujúceho povrchu a mikroštruktúrne zmeny v dôsledku zlyhania implantátu. Analýza 23 extrahovaných polyetylénových vložiek typ Bicon - plus s rozšíreným použitím v Českej republike poukázala na niektoré problémy spojené so zlyhaním implantátu. Adhezívno - abrazívne opotrebenie bolo identifikované v oblasti penetrácie femurálnej hlavice a následné poškodenia ako delaminácia materiálu, plastické deformácie a pitting boli pozorované v okolí tejto oblasti. Analýza materiálových vlastností poukázala na degradáciu mechanických a chemických vlastností, čo bolo prevažne závislé od rozsahu opotrebenia implantátu. U implantátov boli pozorované výrazné plastické deformácie , nárast oxidačného indexu a nižší pomer tvrdosti voči modulu elasticity, v porovnaní s novými vzorkami. Tečenie materiálu a plastické deformácie, ktoré vykazovali všetky extrahované vzorky boli analyzované v závere predloženej dizertačnej práce, na základe testov na nových implantátoch v zábehovom cykle.

Cieľom práce je uviesť nový prístup analýzy opotrebenia polyetylénových vložiek za pomoci optických skenovacích metód a preukázať jeho použiteľnosť na analýze súboru extrahovaných implantátov. Výsledky získané pomocou tejto metódy sa ukázali ako vhodné a môžu viesť k lepšiemu pochopeniu procesov opotrebenia a zlyhávania implantátov.