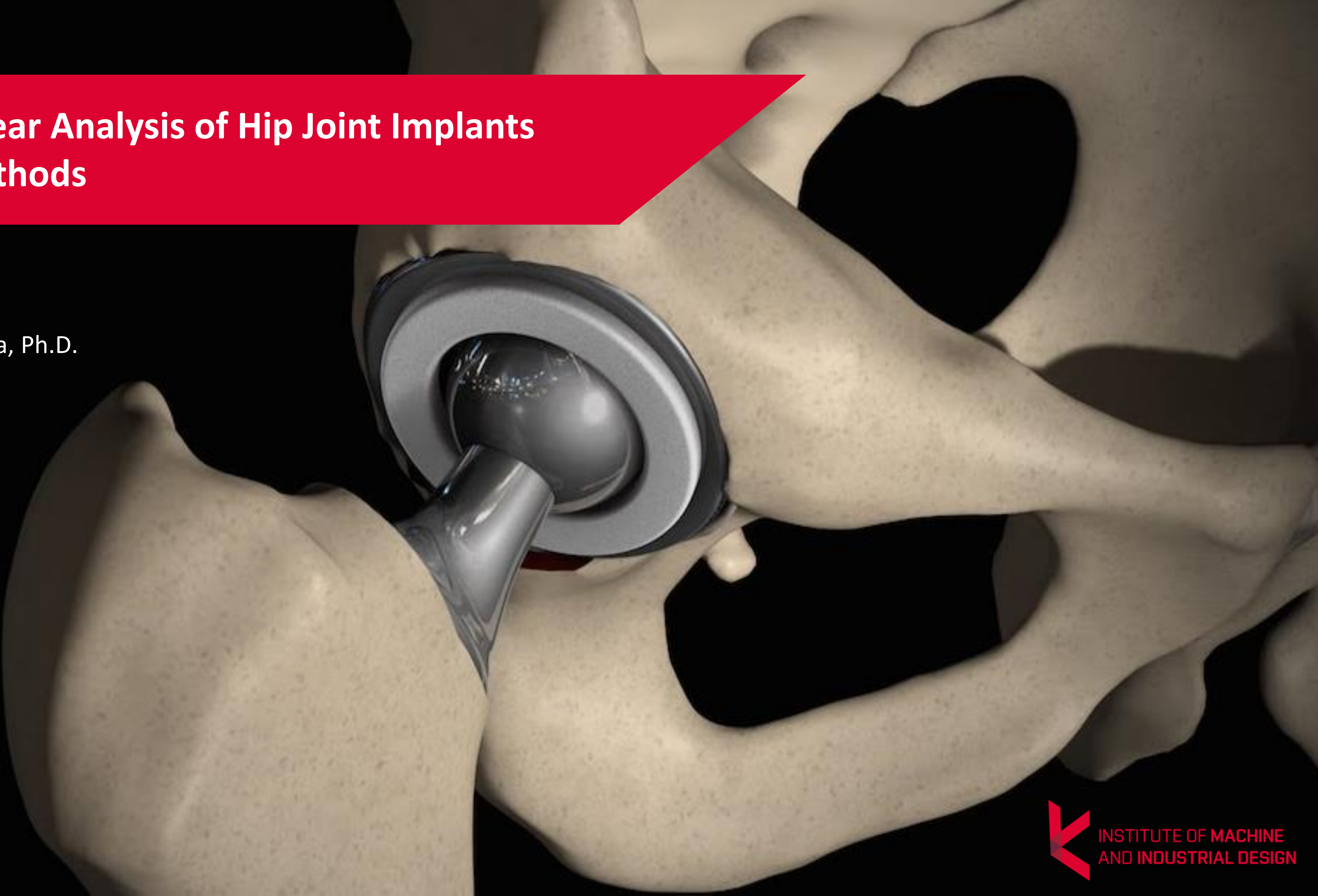
Volumetric Wear Analysis of Hip Joint Implants by Optical Methods

Matúš Ranuša

Doc. Ing. Martin Vrbka, Ph.D.



Ph.D. Defense

Brno, 8th January 2018

INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN

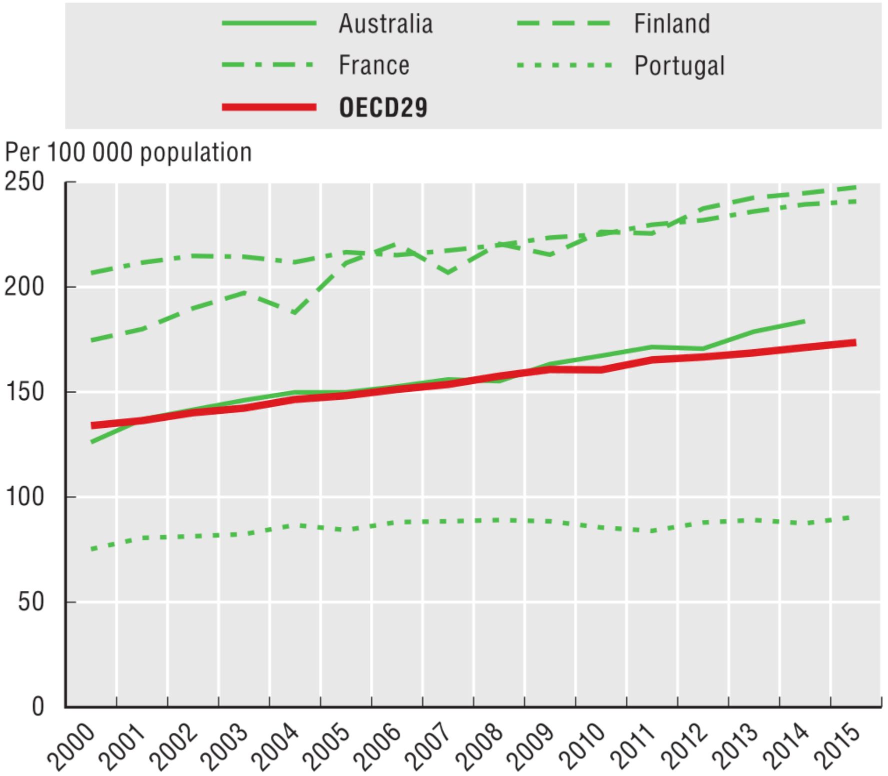
Motivation

101 651
Surgeries / year 2016

NJR for England, Wales, Northern Ireland and the Isle of Man

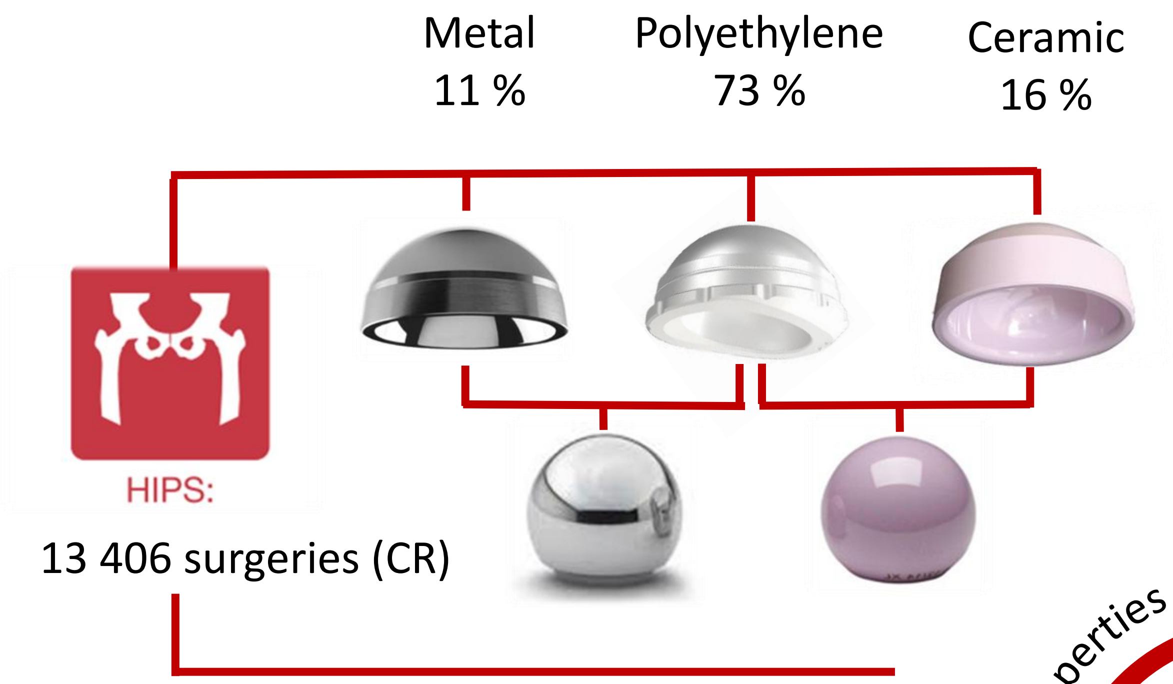
46,4% | 49,66% | 0,4% | 3,18% | 0,3%

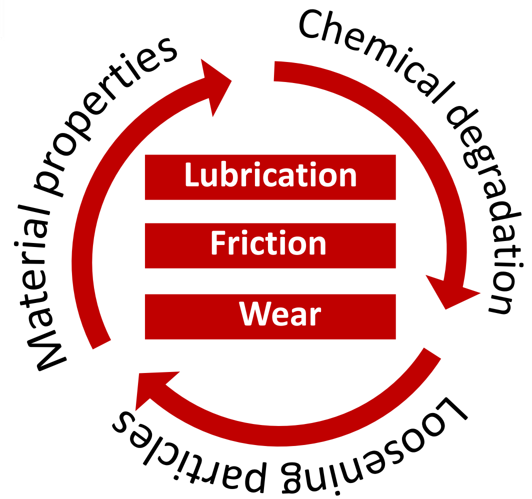
- Total hip replacement
  - Common and most successful surgeries
  - 166 surgeries per 100 000 population (OECD 2016)
  - Limited longevity of implants (5-15 years)
  - Revision surgeries (10%, 2-3 times higher costs)

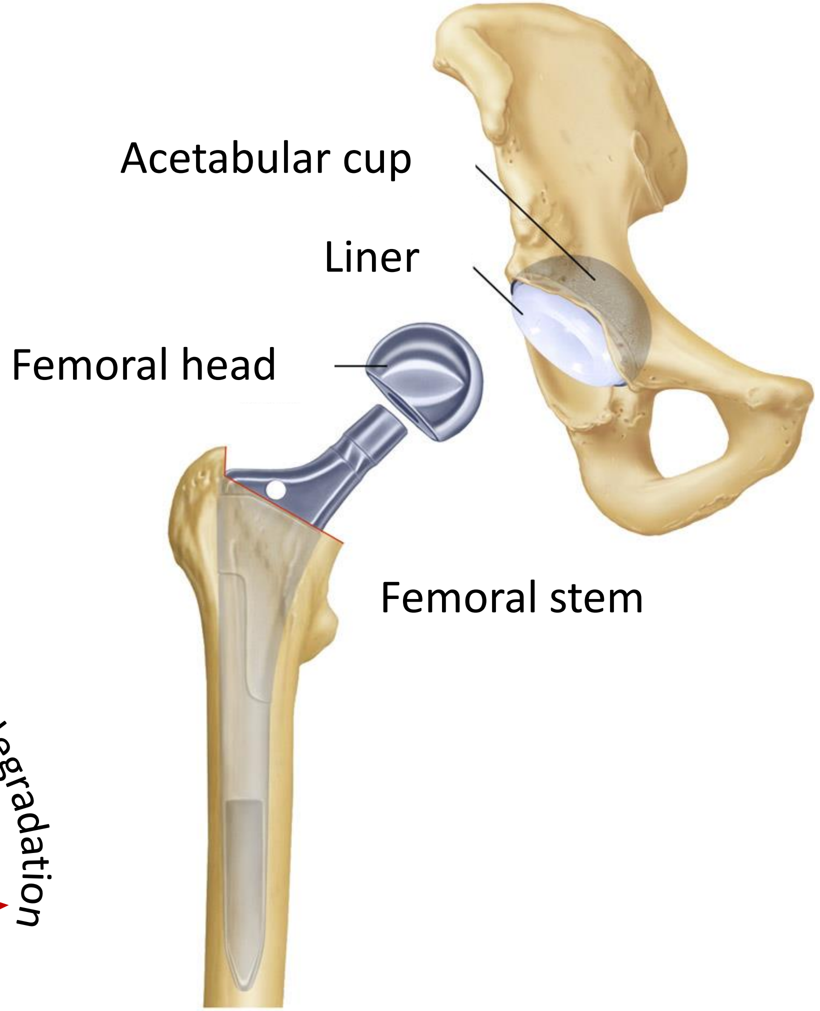


INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN

Biotribology of Hip Joint Implants

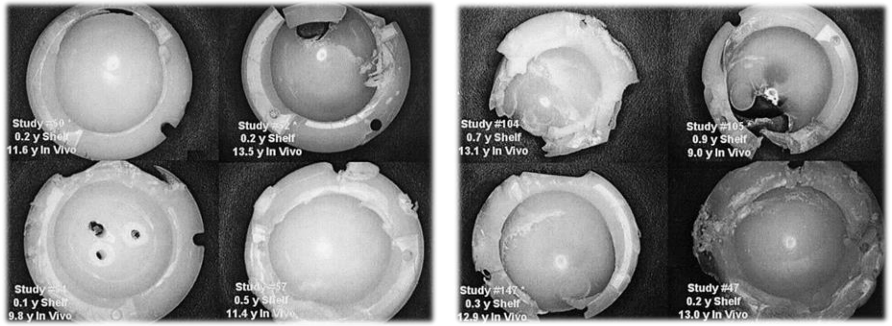


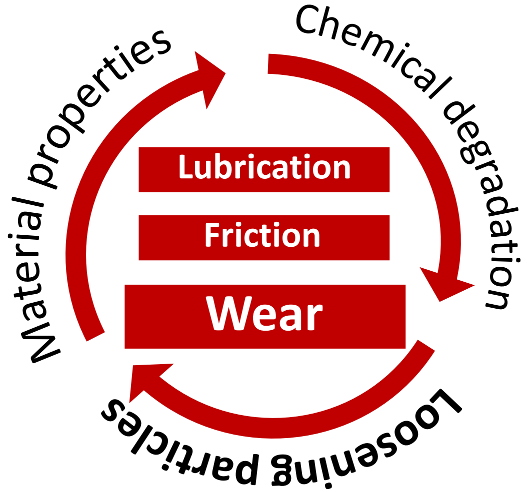




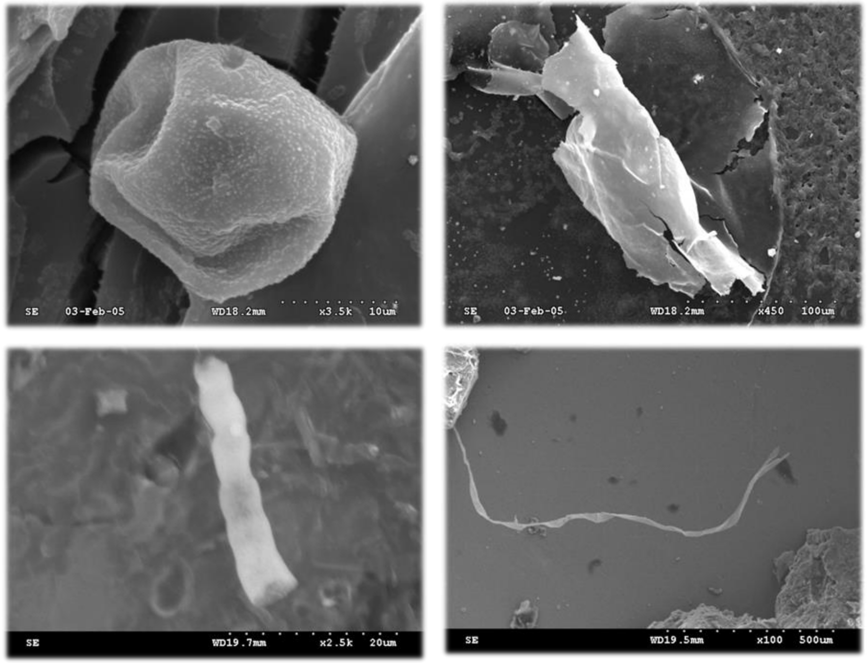
Clinical Aspects of Polyethylene Wear

- Wear of UHMWPE liners
  - Fracture, plastic deformations
  - Loosening of debris





- Aseptic loosening (osteolysis) > 50%



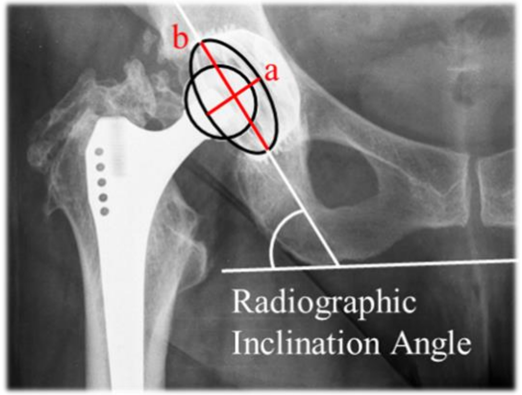
0 - 80 mm³/year	Rare osteolysis
80 - 140 mm³/year	Osteolysis ranging from 6% to 31%
> 140 mm³/year	Osteolysis ranging from 21% to 100%.

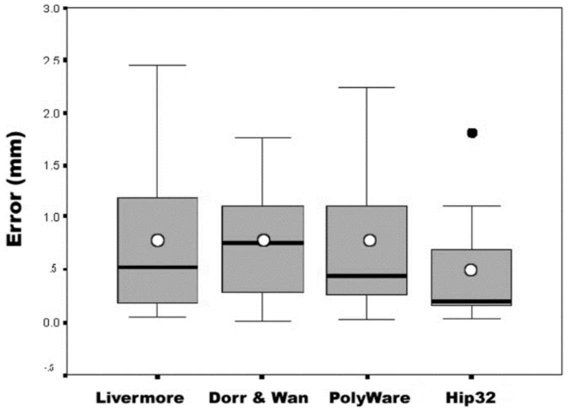
Methods of Wear Analysis – State of the Art

In vivo ← **Analysis of Wear** → **In vitro**

- Radiograph
- Radiostereometric
- Computer Tomography

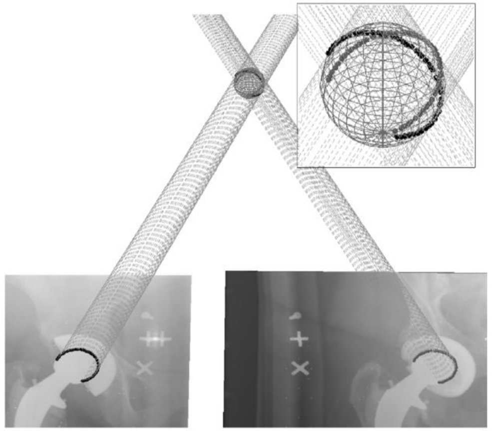
- **Martell et. al** – method Hip32
  - The most widely used method
  - Routine medical examination
  - Result: linear wear
  - Image processing software
  - Accuracy - ± 1 mm (1250 mm^3)

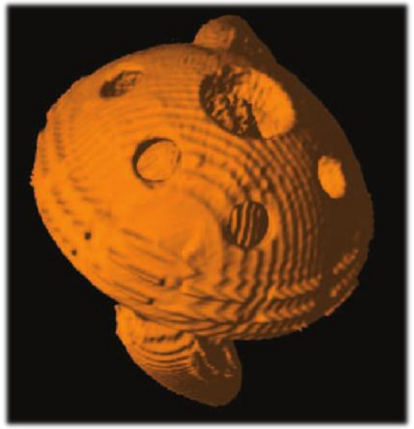




- **Selvik et. al., Clarke et. al.** – Radiostereometric method
  - Result: volumetric wear
  - Accuracy – 30 mm^3

- **Olivecrona et.al.** – Computer tomography
  - Accuracy – ± 0.5 mm (616 mm^3)





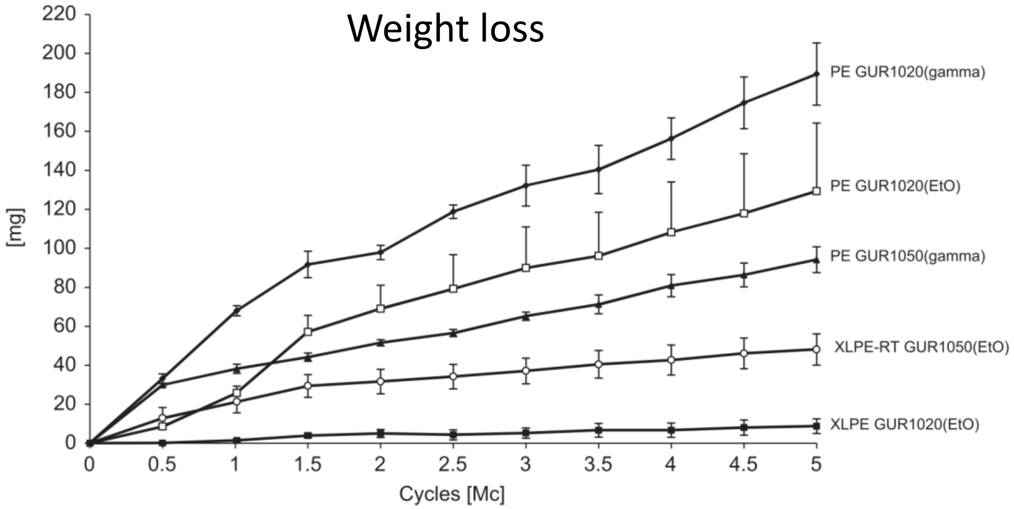
Methods of Wear Analysis – State of the Art

In vivo

Analysis of Wear

In vitro

- **Affatato et.al**, **Smith et. al.....** - Gravimetric
    - Balance resolution: 0.1 mg (equal to 0.1 mm^3)
    - Soak-control recommended by ISO 14552 (2001)
    - For long term wear test and validation of new methods



Gravimetric

Coordinate Measuring Method

Micro CT

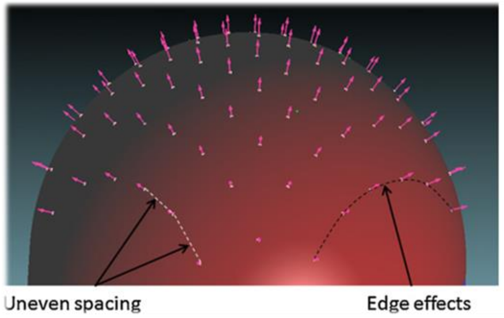
Optical Methods

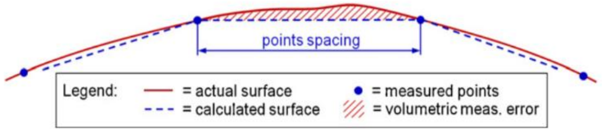
Methods of Wear Analysis – State of the Art

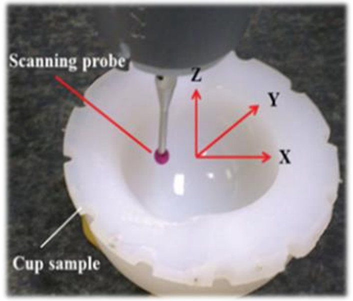
In vivo ← **Analysis of Wear** → In vitro

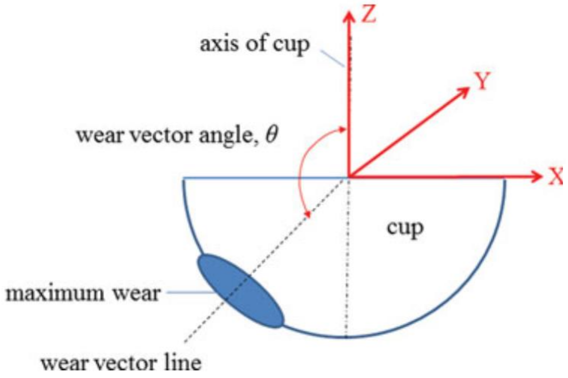
- Gravimetric
- Coordinate Measuring Method
- Micro CT
- Optical Methods

- **Hu et. al, Carmignato et.al, Uddin et.al**
  - Resolution of the measuring machine: 0.1 µm
  - Limited number of measurement points
  - Errors related to polygonization (data post processing)
  - Not suitable for liners with extensive damages









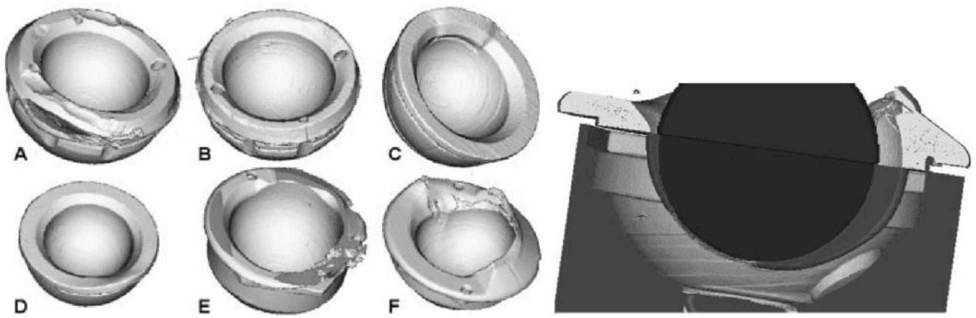
Sample	Nominal Diameter (mm)	Time to Retrieval (years)	Linear Wear (mm) (SD)	Volumetric Wear (mm^3) (SD)	Volumetric Uncertainty, U_v (mm^3)
Cup 1 (XPE)	28.16	3	0.07 (0.001)	14.02 (0.48)	1.82
Cup 2 (XPE)	36.32	10.5	0.10 (0.004)	10.30 (4.39)	3.12
Cup 3 (X3)	36.08	4	0.07 (0.006)	13.01 (6.21)	3.12
Cup 4 (X3)	32.12	6	0.05 (0.000)	7.24 (0.50)	2.62
Cup 5 (X3)	28.16	—	0.05 (0.006)	0.49 (0.41)	1.82

Methods of Wear Analysis – State of the Art

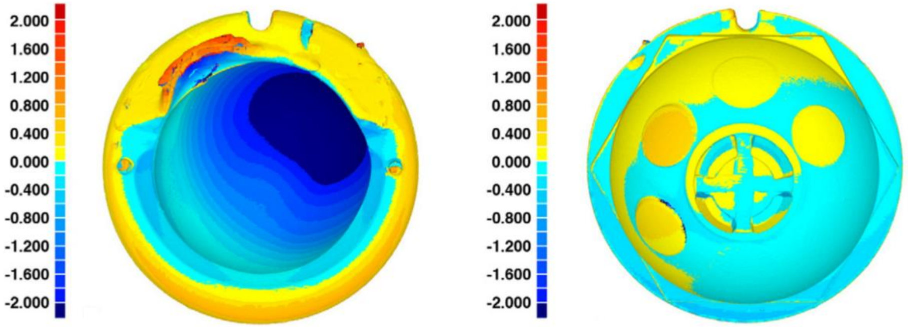
In vivo ← **Analysis of Wear** → In vitro

In vitro:
- Gravimetric
- Coordinate Measuring Method
- **Micro CT**
- Optical Methods

- **Bowden et. al.** - Micro CT
  - Resolution of measurement: 0.075 mm
  - 588 mm^3 (range: 74–1331 mm^3/year)
  - Difficult postprocessing of results



- **Teeter et. al.** - Micro CT
  - Resolution of measurement: 0.05 mm
  - Noncontact method, scanning time: 95 min
  - Difficult to measure low volumes of wear
  - Results of measurement - volume

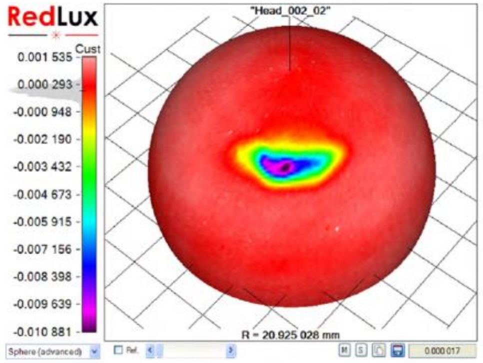


Methods of Wear Analysis – State of the Art

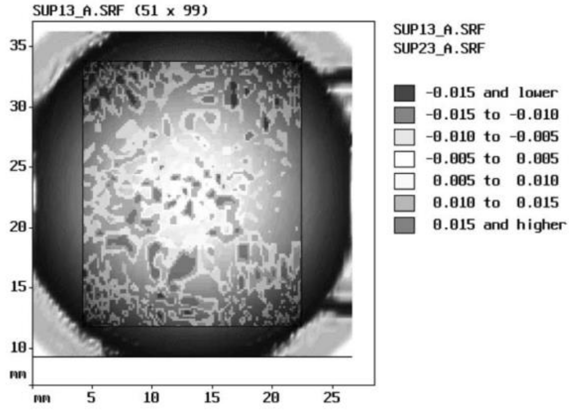
In vivo ← **Analysis of Wear** → In vitro

- Gravimetric
- Coordinate Measuring Method
- Micro CT
- **Optical Methods**

- **Tuke et. al.** - Optical methods – RedLux
  - Noncontact method
  - Chromatically encoded confocal light
  - Results of measurement with surface accuracy of 0.033 mm^3



- **Zou et. al.** – Sequential hemisphere scanning
  - Laser probe – resolution 1µm with CMM
  - Principle of optical triangulation
  - Reproducibility 1.41mm^3



Summary of Literature Review

In vivo methods

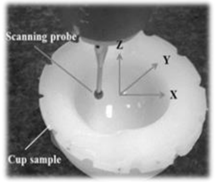
Radiographs

- Observation in body
- Available during the lifecycle of the implant

- Inaccuracy of measurement < 1 mm

In vitro methods

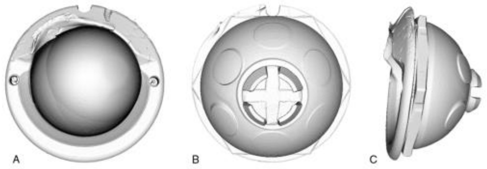
CMM



- Accuracy > 1 µm
- ISO standardization

- Number of points
- Postprocessing errors
- Contact method

Micro CT



- Volumetric output
- Time effeciency - 95 min
- Noncontact method

- Accuracy – 50 - 70 µm
- Costs

Optical methods

- Effective postprocessing
- Large number of surface points
- Damage reconstruction
- Noncontact method

- Accuracy of measurement
- Stitching of scans
- Coating application

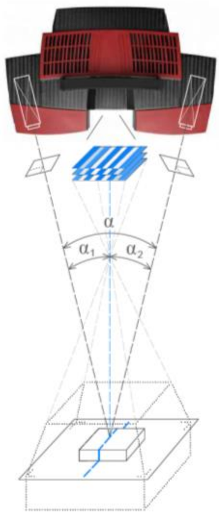
New optical method:

- Time efficiency < 20 min
- Analysis of linear and volumetric wear
- Accuracy of measurement < 0.01 mm
- Reconstruction of damages – large number of points > 200 000

Aim of Thesis

Aim of the thesis is to establish a new approach for volumetric wear assessment for acetabular polyethylene liners using optical methods.

Scanning method → **Validation** → **Creep analysis** → **Surface analysis** → **Evaluation on retrievals**



Scanner – ATOS Triple scan

Pendulum

Custom hip simulator

Bruker Contour X6

Extracted liners

Scientific Questions

Scientific questions

Q1: How can the accuracy of the optical scanning method 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?

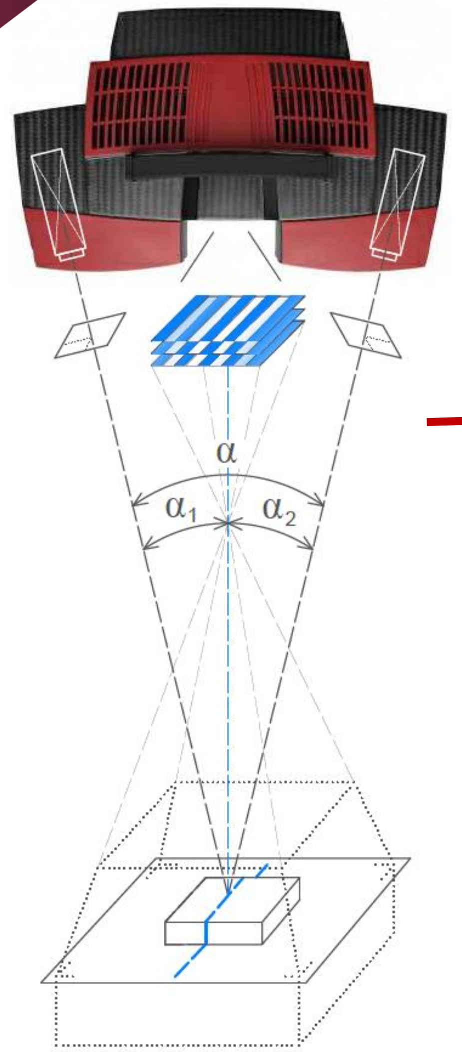
Hypotesis

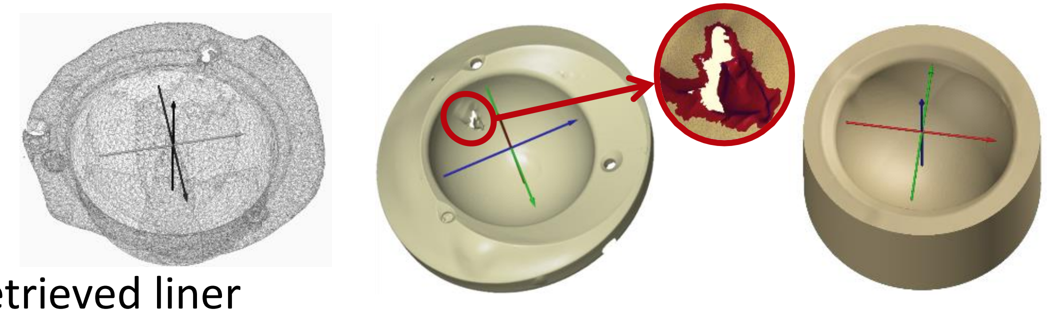
H1: The optical method will be able to approximate the original surface geometry with a better accuracy than current methods and hence will be more accurate in determining the wear.

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 plastic deformations due to decreasing contact pressure in the articulating area.

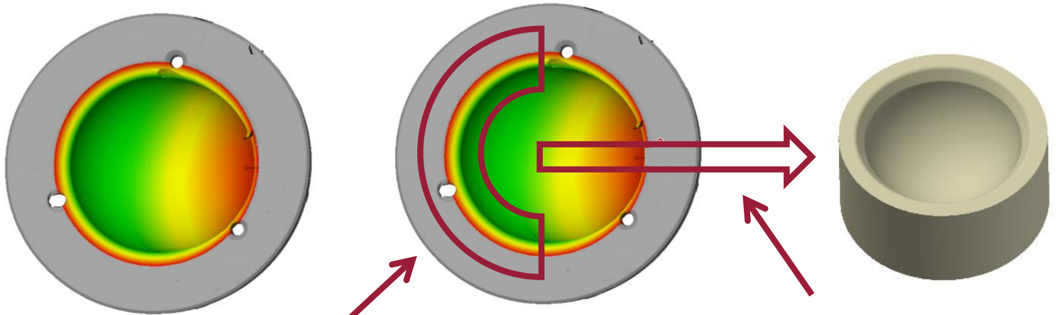
Material and Methods

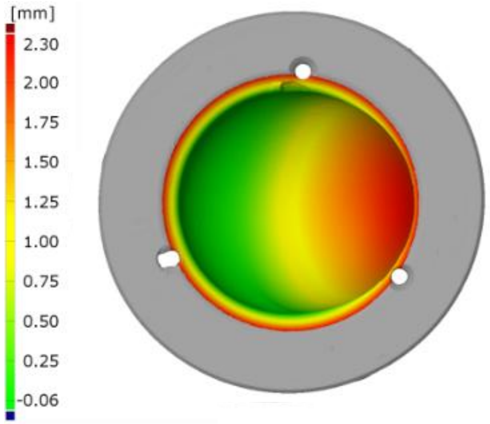


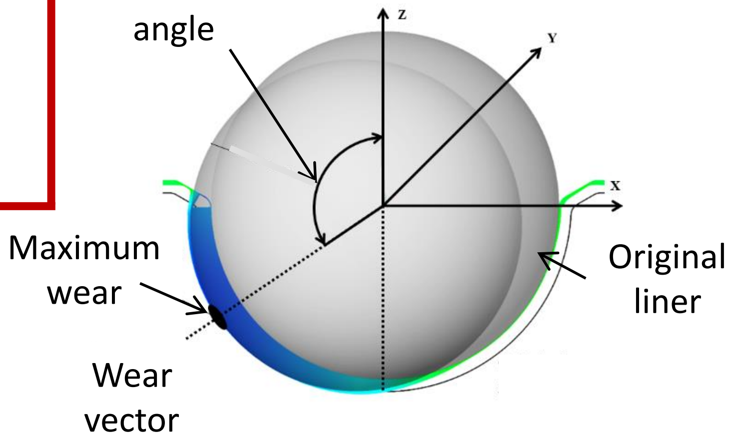


Retrieved liner

- Point cloud (200 000 points)
- Reconstruction of extraction damages
- Identification of unworn parts – calculation of original diameter







Material and Methods

Pendulum
- Frequency 1 Hz
- Load 2500 N
- Flexion extension movement

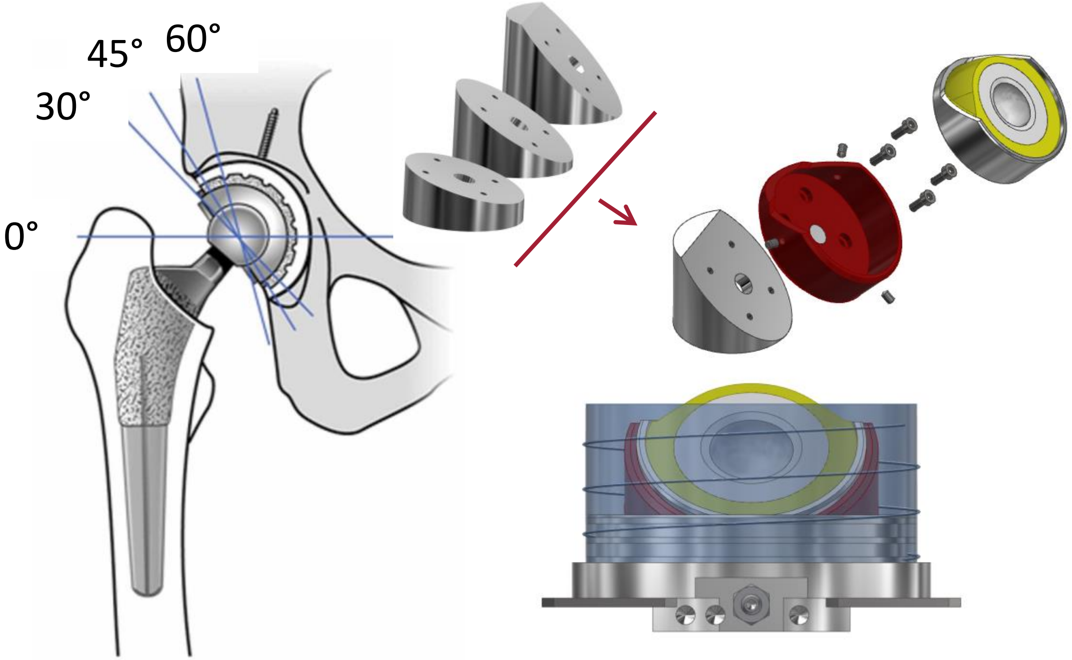
3x UHMWPE liner
- Avarage material loss 0.075g
- Total volume wear 80 mm^3

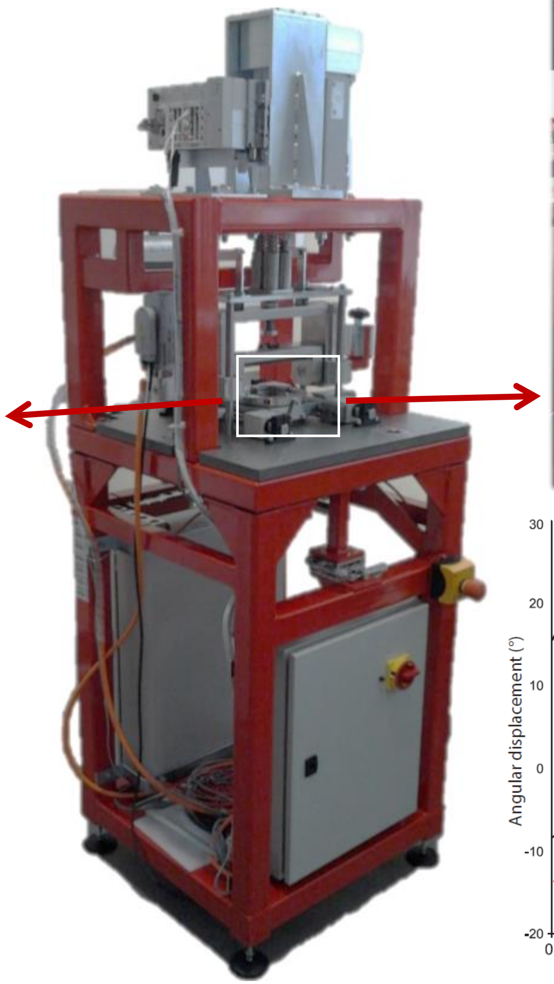
Gravimetric comparison
- Optical scanning method
- Gravimetric – Balance 0.1 mg

Material and Methods

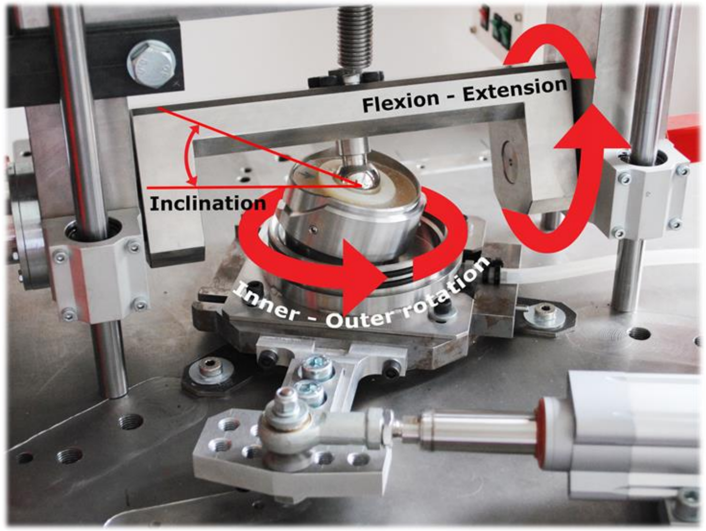
Scanning method → Validation → Creep analysis → Surface analysis → Evaluation on Retrievals

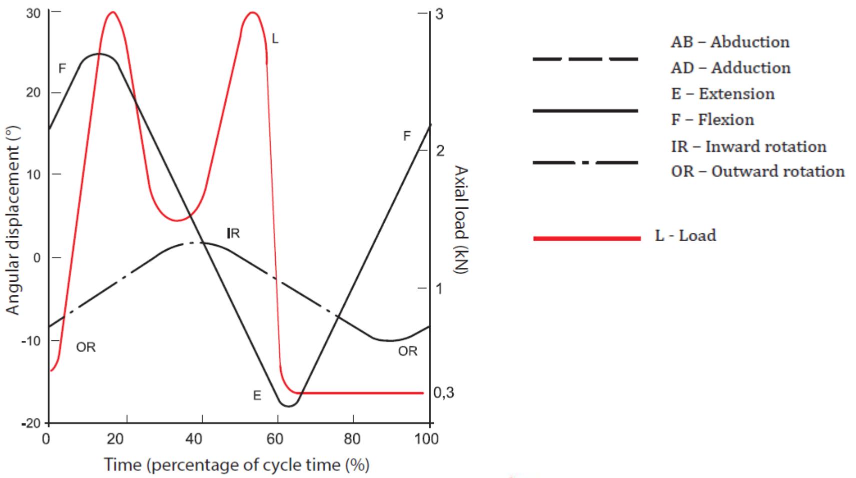
- Plastic deformation analysis
- 2 DoF- phase shifted cycles ISO 14552
- Lubricant – model synovial fluid, 37°C
- Three inclination angles investigated
- Run-in-phase established 50 000 cycles





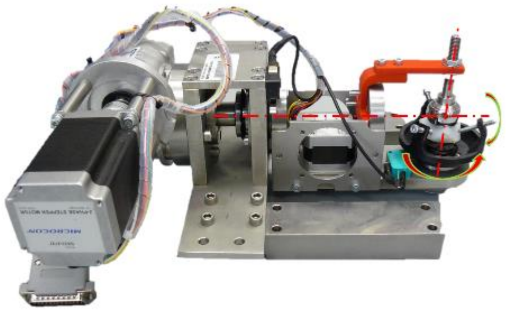
Custom made hip simulator



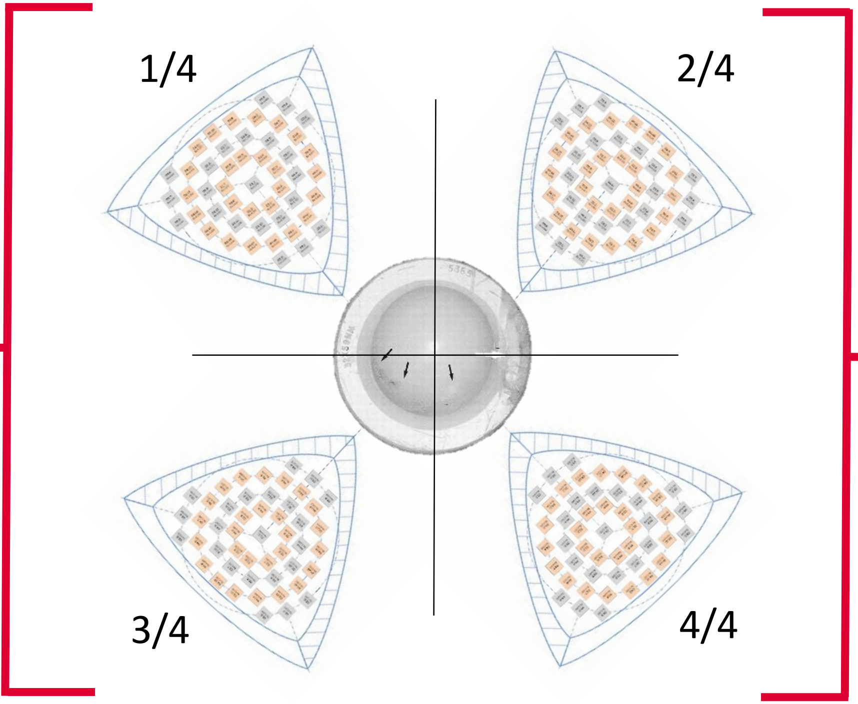


Material and Methods

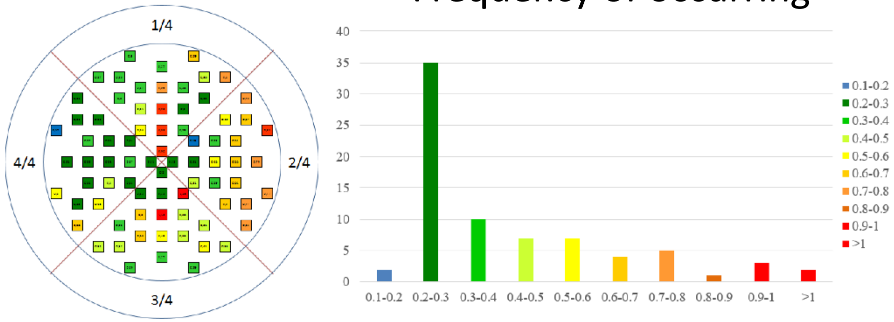
Profiler Bruker



Custom made positioning stage



Frequency of occurring



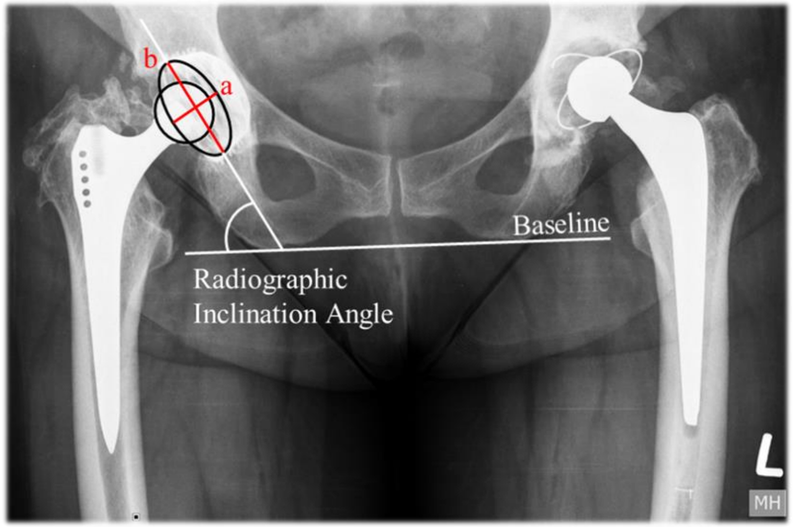
Roughness of wear areas

- Measured area 0.5 mm^2
- Readability 1 nm
- 79 measurement of roughness
- Sorted by frequency of occurrence

Material and Methods

Scanning method → Validation → Creep analysis → Surface analysis → Evaluation on Retrievals

- 18 extracted acetabular cups, type Bicon plus
- Nominal diameter: 28 mm
- Manufacturer Material: UHMWPE
- Revision surgeries between 2010-2015
- Survival time in situ: 9.1 years
- Analysis of Radiographs – abduction angle

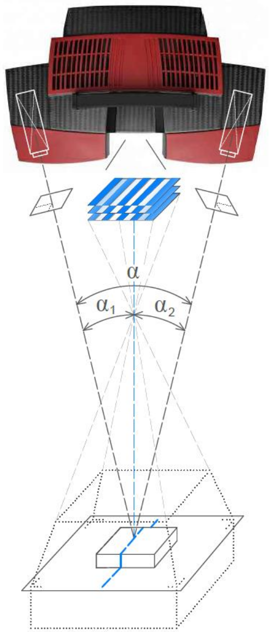


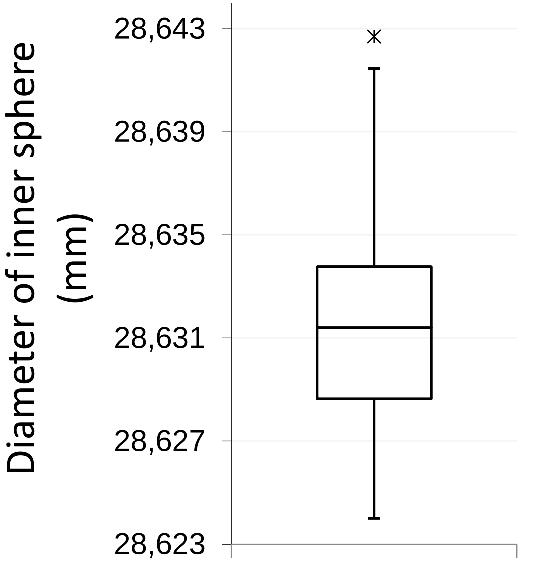
Patient (No.)	Gender	Height (cm)	Weight (kg)	Side	Orientation after primary surgery	The survival of the prosthesis (years)	Reason of Revision
1	m	165	66	R	50.6	12.06	Fracture, osteolysis
2	f	158	48	R	35.5	10.50	Aseptic loosening
3	f	165	75	L	35.7	10.59	Painful hip, aseptic loosening
4	f	162	63	R	48	10.96	Painful hip, aseptic loosening
5	m	178	103	R	46.4	6.23	Painful hip
6	f	160	88	R	46	4.03	Painful hip, aseptic loosening
7	m	180	100	L	48	7.36	Aseptic loosening
8	f	166	58	L	34	7.77	Fracture
9	f	155	56	R	51	13.67	Painful hip, aseptic loosening
10	f	164	72	R	35.5	4.47	Painful hip, aseptic loosening
11	f	169	77	L	63	5.16	Painful hip, aseptic loosening
12	f	165	60	P	40	3.58	Painful hip, aseptic loosening
13	f	153	68	L	39	9.55	Painful hip, aseptic loosening
14	f	159	56	L	46	4.95	Painful hip, aseptic loosening
15	f	165	85	R	55	12.32	Painful hip
16	f	160	80	R	42	15.55	Wear
17	m	179	78	L	49	10.60	Aseptic loosening
18	m	186	92	L	55	11.47	Aseptic loosening

Results

Repetability of measurement

- Standard deviation 5 µm

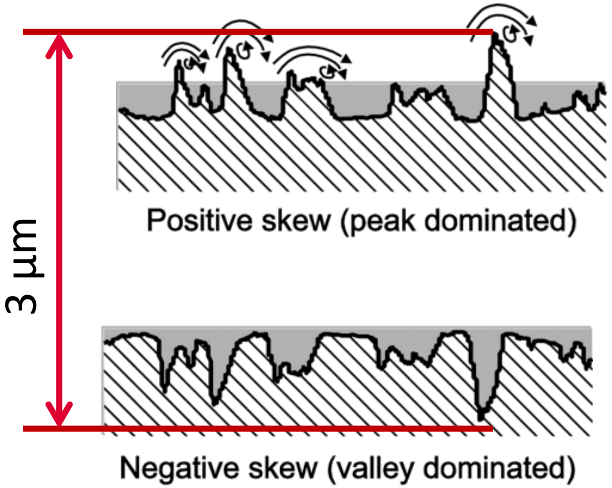




Gaussian (3 sigma)

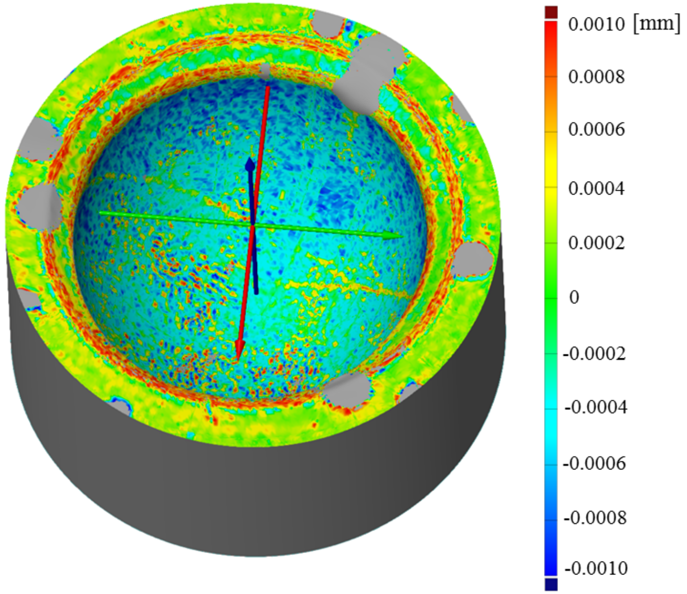
Smoothening of data

- **3 µm**
- Estimation of max volume error – **2.5 mm³**



Comparison surface – polygon data

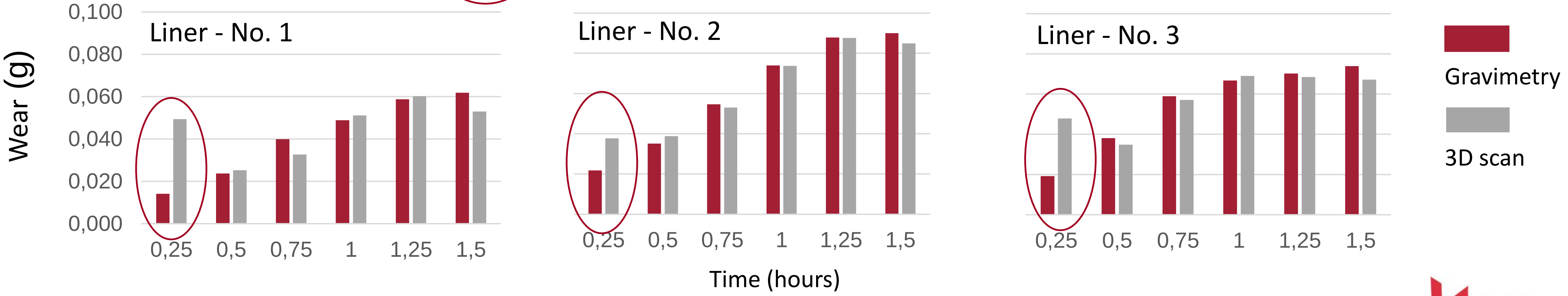
- Error ± **1.5 µm**



Results

- Difference between gravimetric and scanning **28 mm³** (Bevill et. al.20 – 30 mm³)
- Suitalble for higher wear volumes
- Further investigation of creep

Method	Wear Amount (mm^3)					
	No.1	No.2	No.3	No.4	No.5	No.6
Mean wear (mg)	14.18	23.70	39.90	48.86	58.82	61.88
Mean gravimetric (mm^3)	19.60	34.44	54.50	67.36	77.04	80.18
Mean sken (mm^3) , SD	47.84 (8.5)	35.10 (3.1)	50.65 (2.8)	68.77 (1.3)	76.69 (1.4)	72.72 (1.7)
Difference (mm^3)	-28.27	-0.72	3.76	-1.52	0.22	7.34
Normalized error, En (mm^3)	2.92	0.13	0.60	0.18	0.11	0.75
Difference	156.7 %	2.9 %	8 %	2.6 %	0.1 %	9.7 %



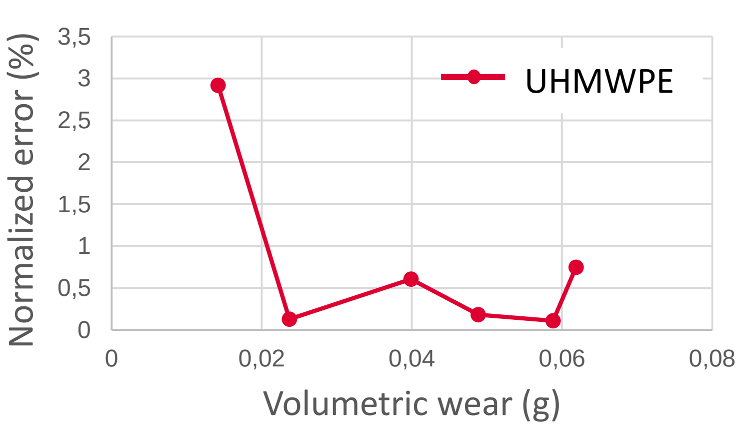
INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN

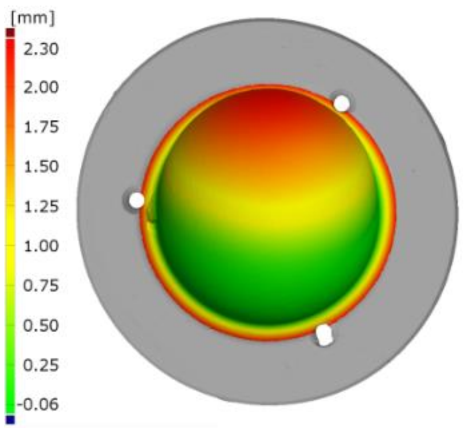
Results

Volumetric wear

Ranuša et. al. (published 2017, CR)

- Time efficiency – 20 min
- Errors less than **10 %** after run-in-phase
- Error of measurement **± 1.57 mm^3**
- Contribution of creep **15 – 23 mm^3**
- Contribution of surface roughness up to **2.5 mm^3**

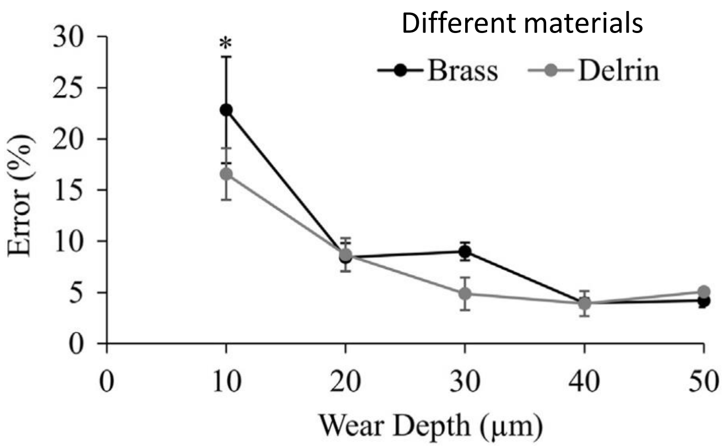


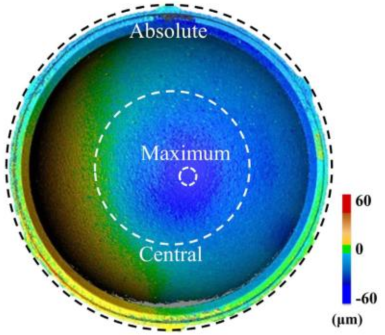


Linear wear

Hollar et. al. (published 2018, USA)

- Analysis of deformations
- Time efficiency – 20 min
- Errors less than **10%**
- Results with accuracy of **2.1 µm**

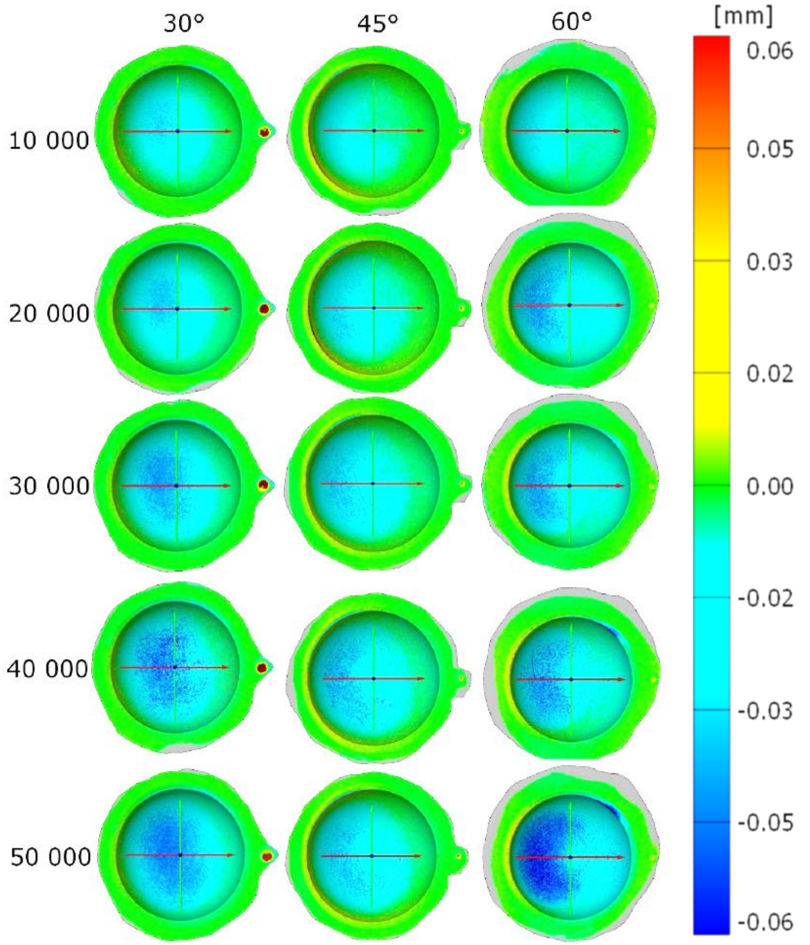


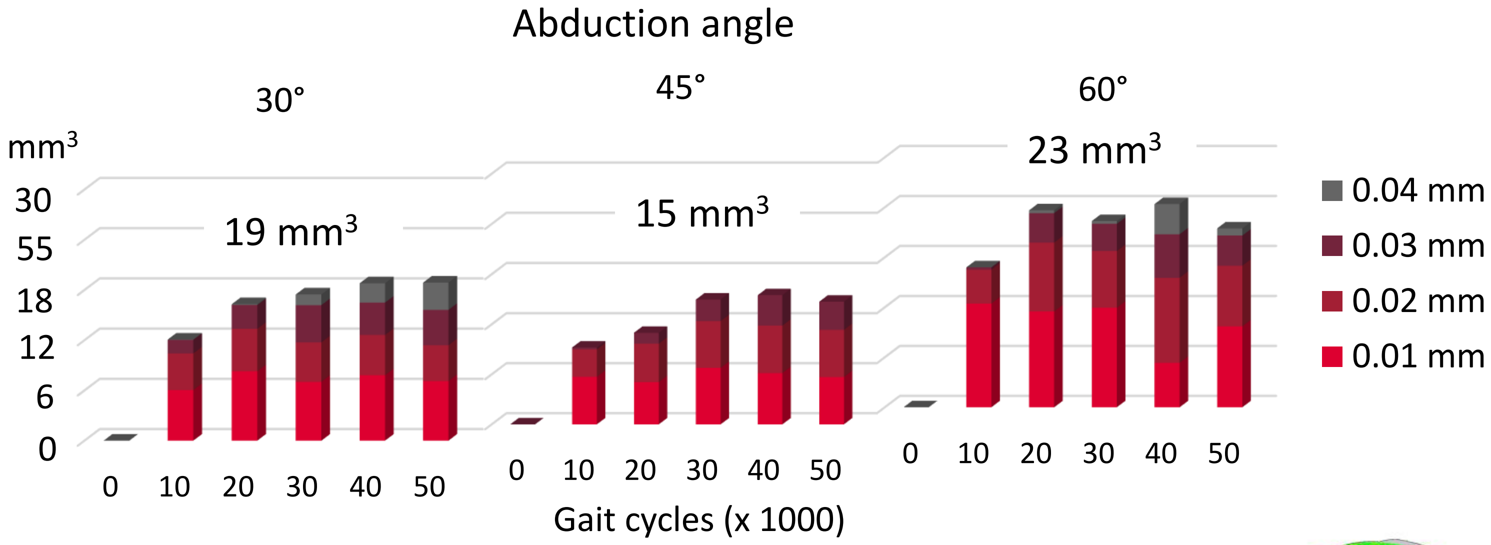


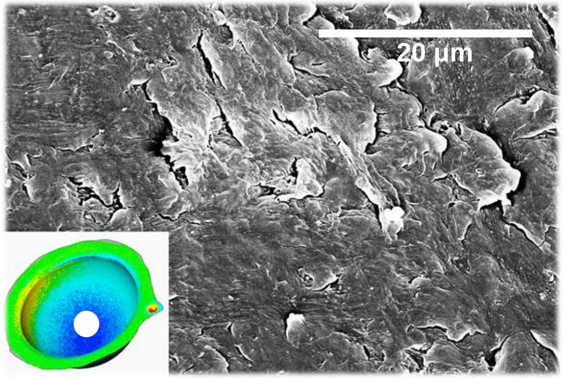
INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN

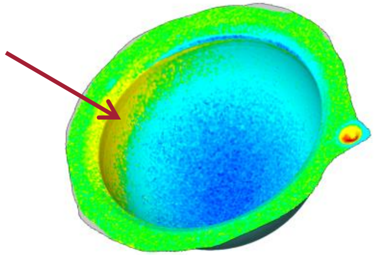
Results

Scanning method → Validation → Creep analysis → Surface analysis → Evaluation on Retrievals







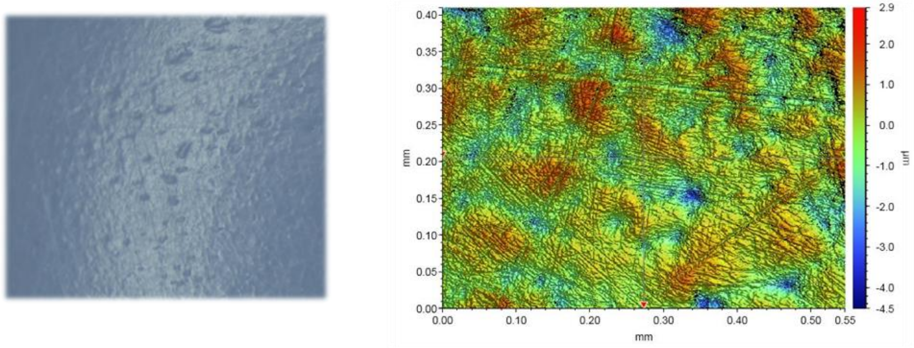


Run – in- phase

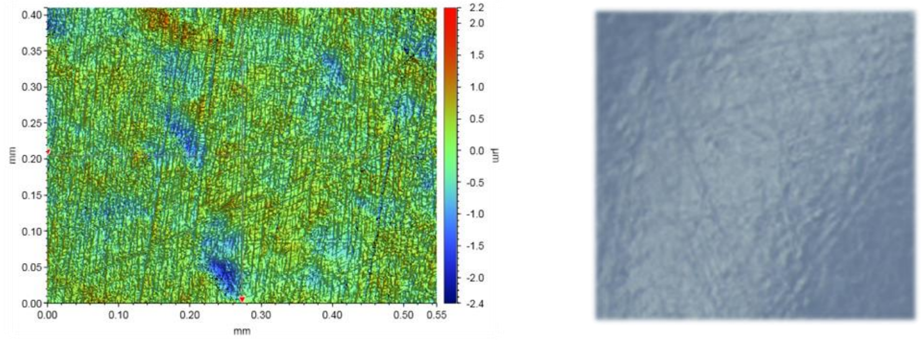
- 50 000 cycles
- Plastic deformation **15 – 23 mm^3**
- Elevated rim **0.04 mm**

Results

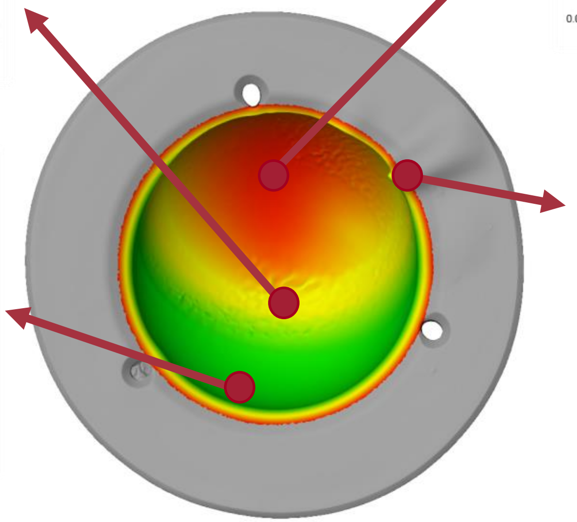
Scanning method → Validation → Creep analysis → Surface analysis → Evaluation on Retrievals

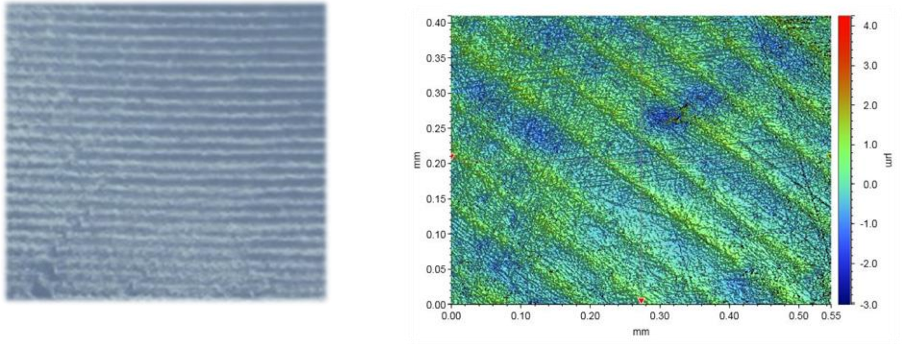


Fatigue wear (0.5 – 2 µm)

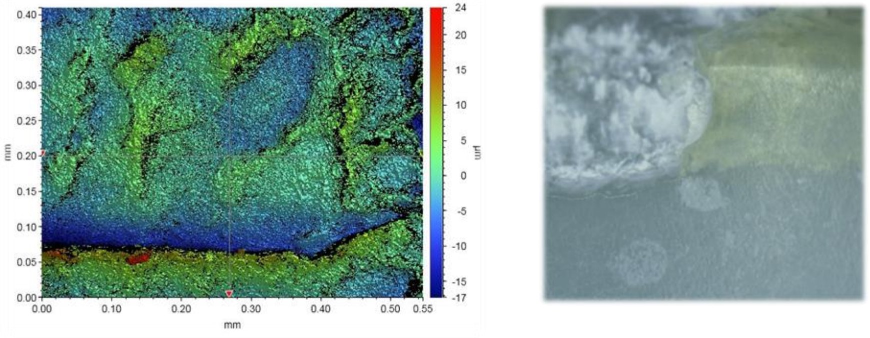


Smoothened surface (0.1 – 0.3 µm)





Original unworn surface (0.3 – 1 µm)

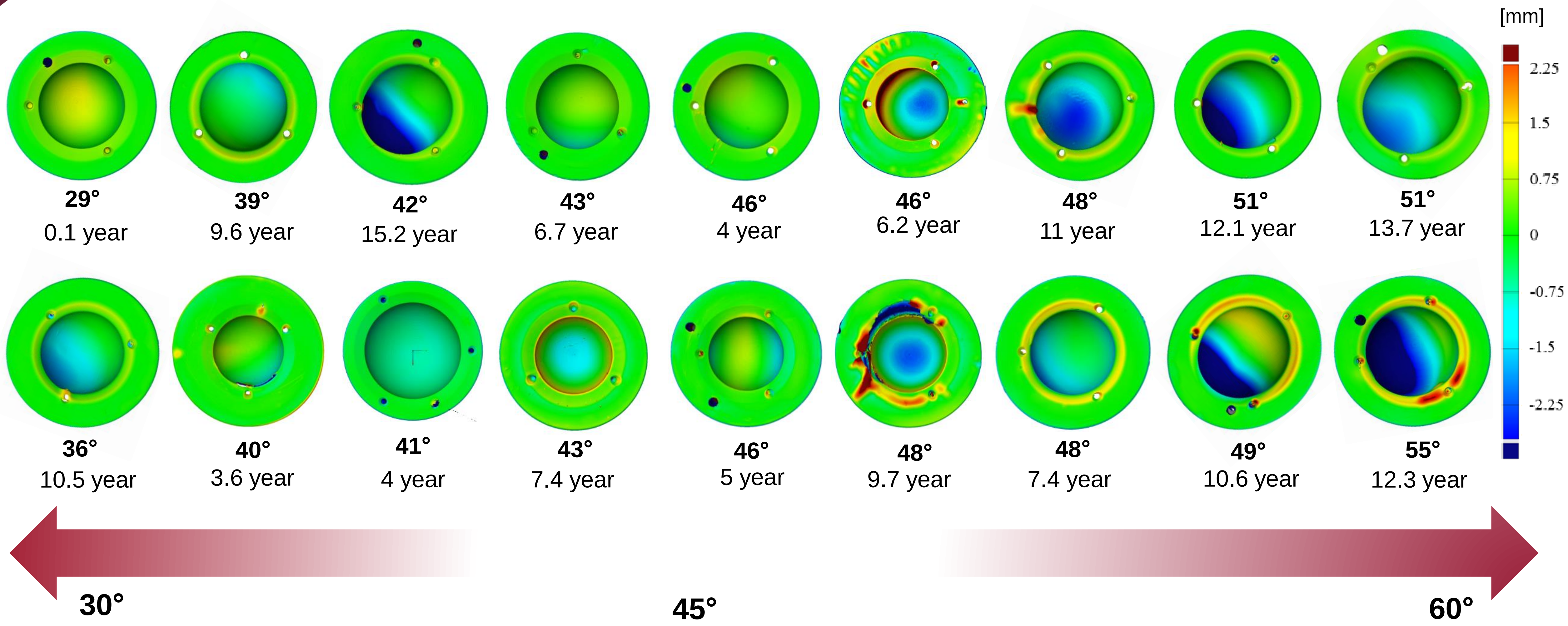


Delamination (0.5 – 10 µm)

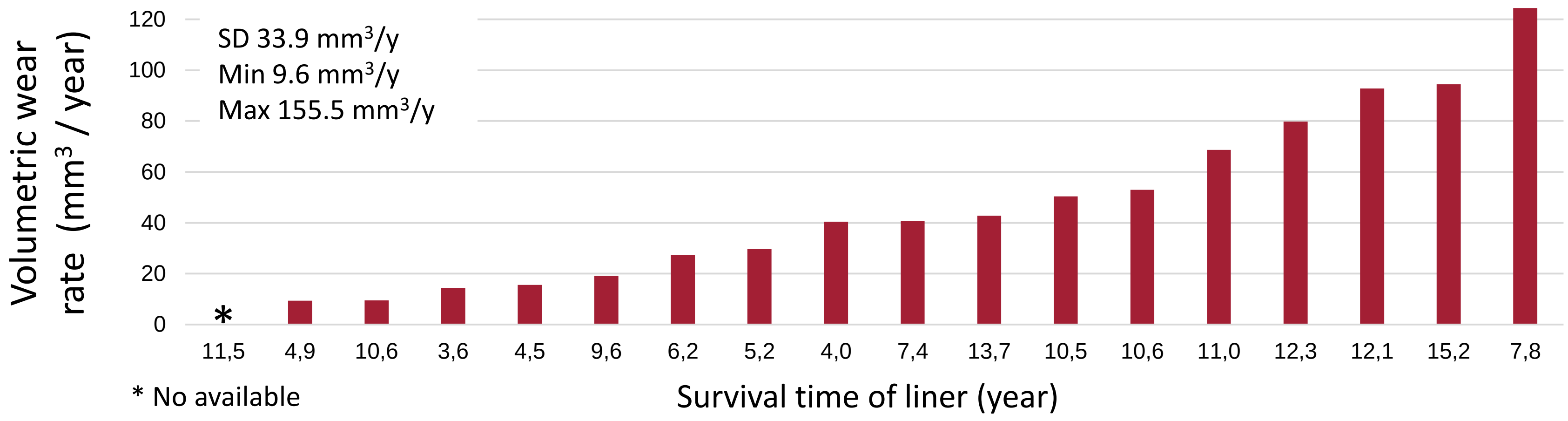
Influence on wear analysis – max **2.5 mm^3**

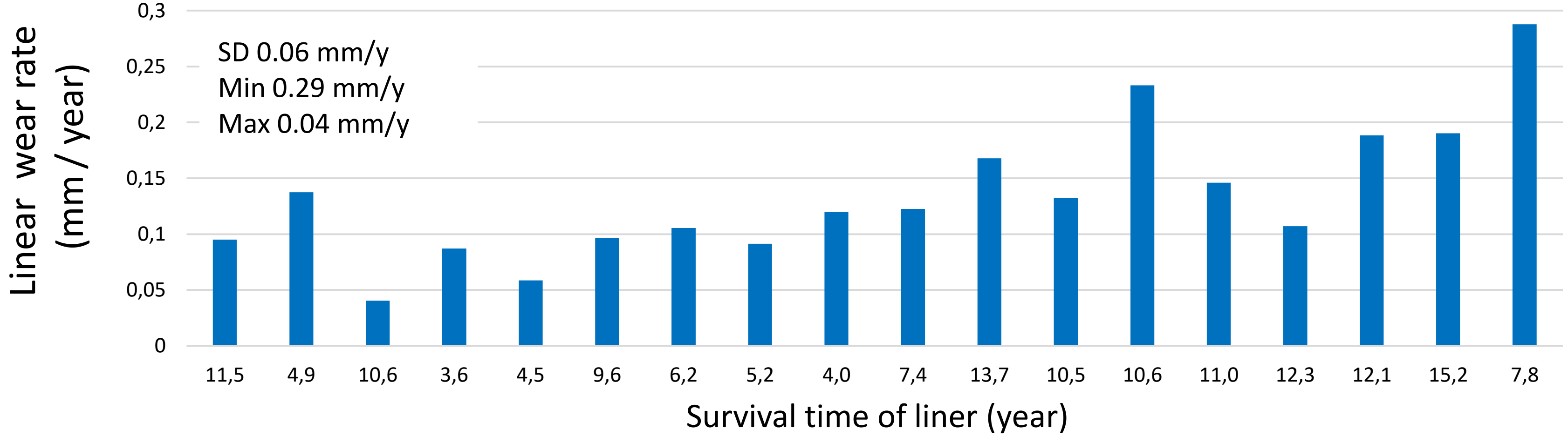
Results

Scanning method → Validation → Creep analysis → Surface analysis → Evaluation on Retrievals



Results



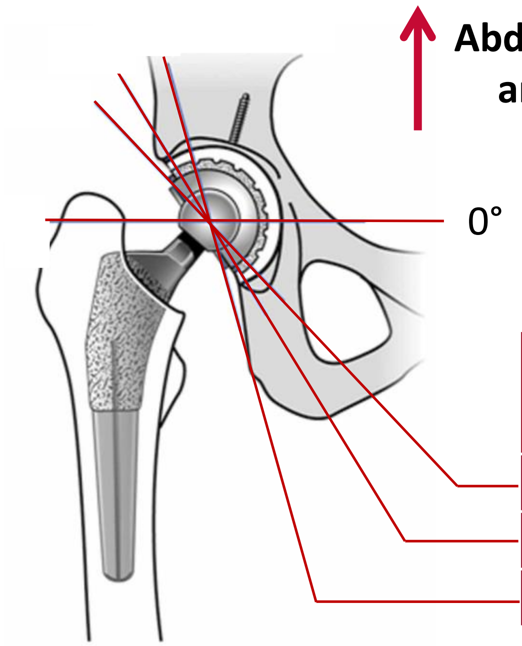


- Survival time **3.6 – 15.3 year**
- Volumetric wear **46 – 1439 mm³**
- Influence of other factors
- Linear wear **0.26 – 2.9 mm**
- Differences between linear and volumetric wear

Limitations

- Number of retrieved liners
- New generation of materials
- Influence of abduction angle
- Back-side wear

Discussion – Wear and Degradation of UHMWPE



Abduction angle	Plastic deformation (mm^3)	Coefficient of friction	Contact pressure (MPa)	Contact area (mm^2)
60°	23	0.135	17.5	280
45°	15	0.170	11	340
30°	19	0.160	7	390

Ranusa et.al Korduba et.al

Retrievals

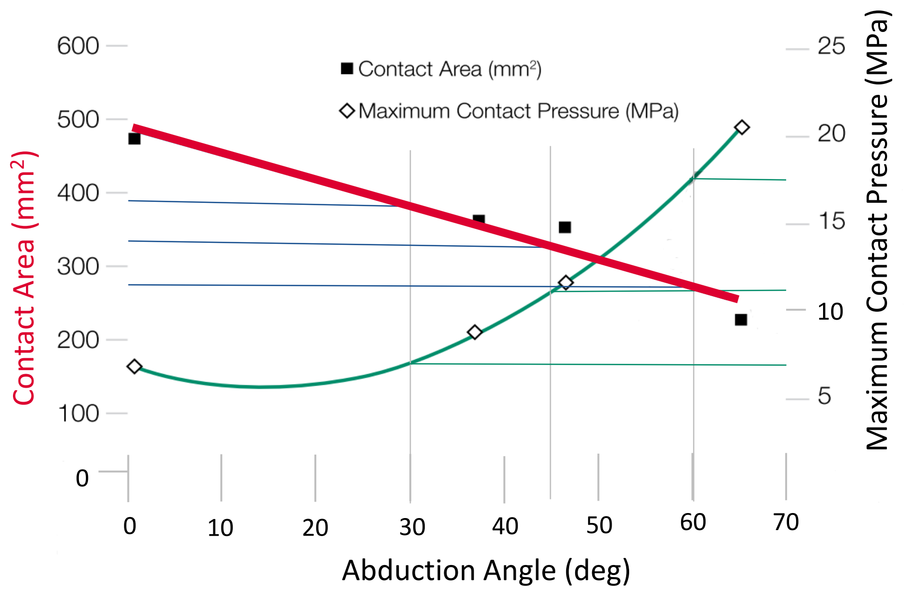
- Number of factors influencing volumetric wear

Plastic deformations

- Role of abduction angle

Korduba et al., 2014

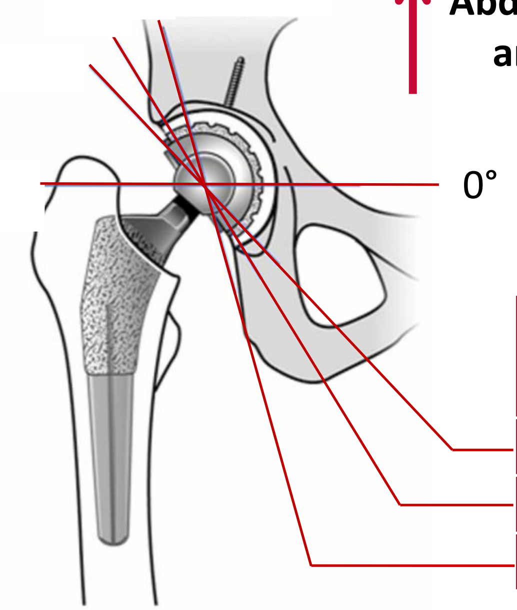
FEM analysis, Effect of acetabular cup abduction angle on wear of UHMWPE in hip simulator testing



INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN

Discussion – Wear and Degradation of UHMWPE

↑ **Abduction angle** ↓ Contact area ↑ **Contact pressure**

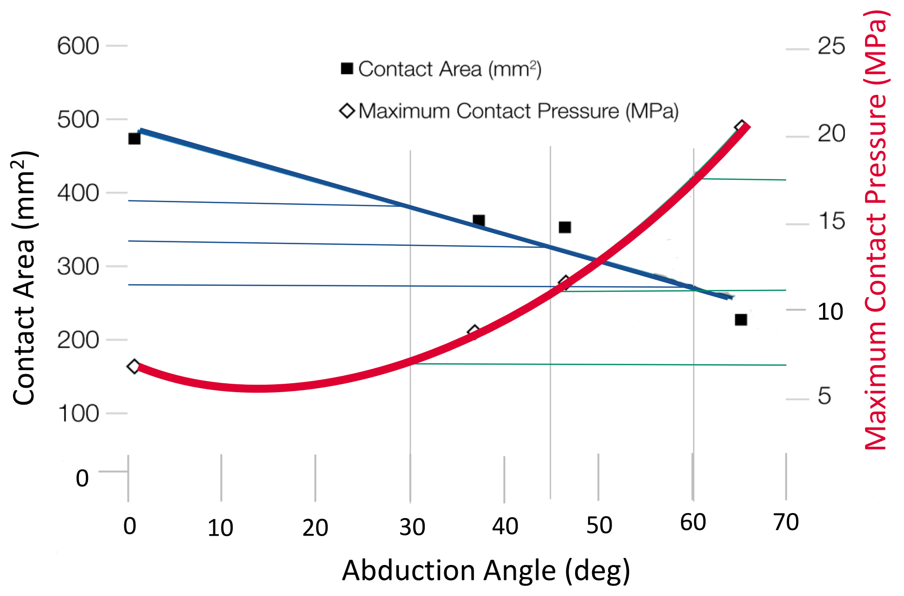


Abduction angle	Plastic deformation (mm^3)	Coefficient of friction	Contact pressure (MPa)	Contact area (mm^2)
60°	23	0.135	17.5	280
45°	15	0.170	11	340
30°	19	0.160	7	390

Ranusa et.al Korduba et.al

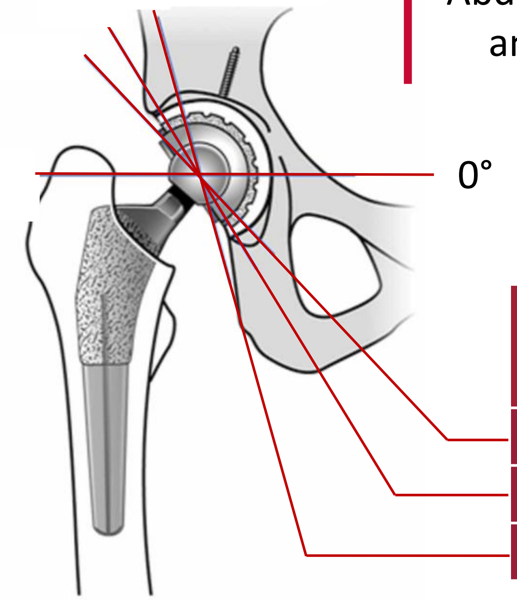
Korduba et al., 2014

FEM analysis, Effect of acetabular cup abduction angle on wear of UHMWPE in hip simulator testing



Discussion – Wear and Degradation of UHMWPE

↑ Abduction angle ↓ Contact area ↑ **Contact pressure** ↓ **Wear**

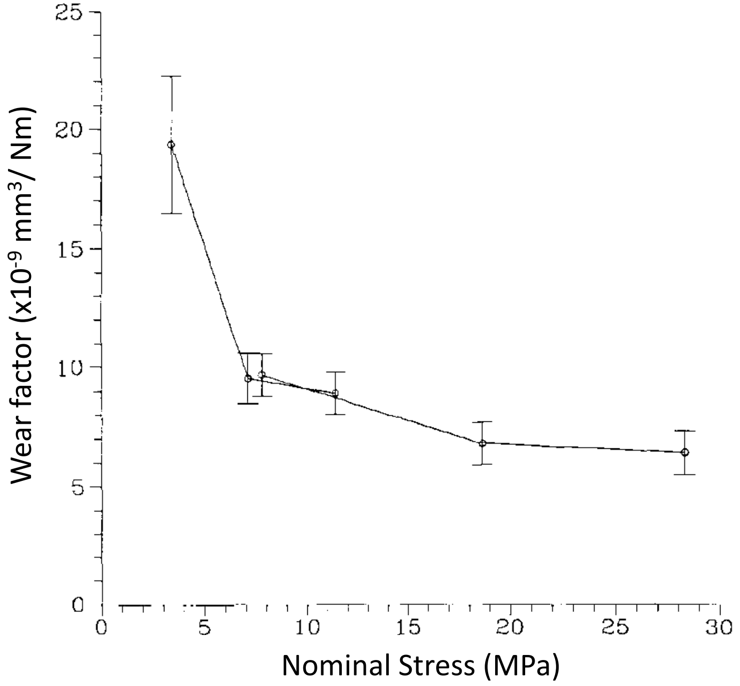


Abduction angle	Plastic deformation (mm^3)	Coefficient of friction	Contact pressure (MPa)	Contact area (mm^2)
60°	23	0.135	17.5	280
45°	15	0.170	11	340
30°	19	0.160	7	390

Ranusa et.al Korduba et.al

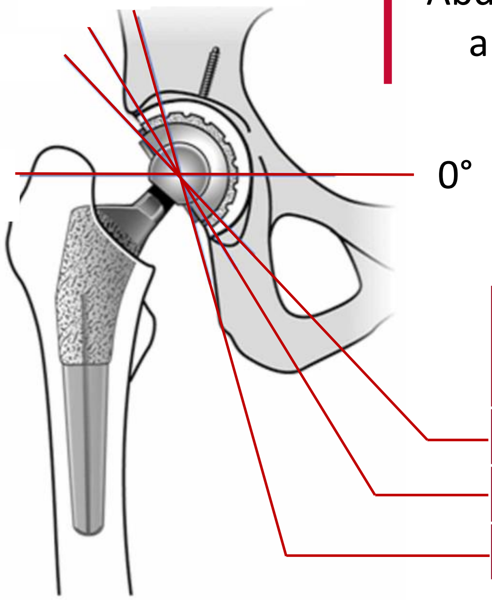
Barbour et al., 2014

The influence of contact stress on the wear UHMWPE for total replacement hip prostheses



Discussion – Wear and Degradation of UHMWPE

↑ Abduction angle ↓ **Contact area** ↑ Contact pressure ↓ **Wear**

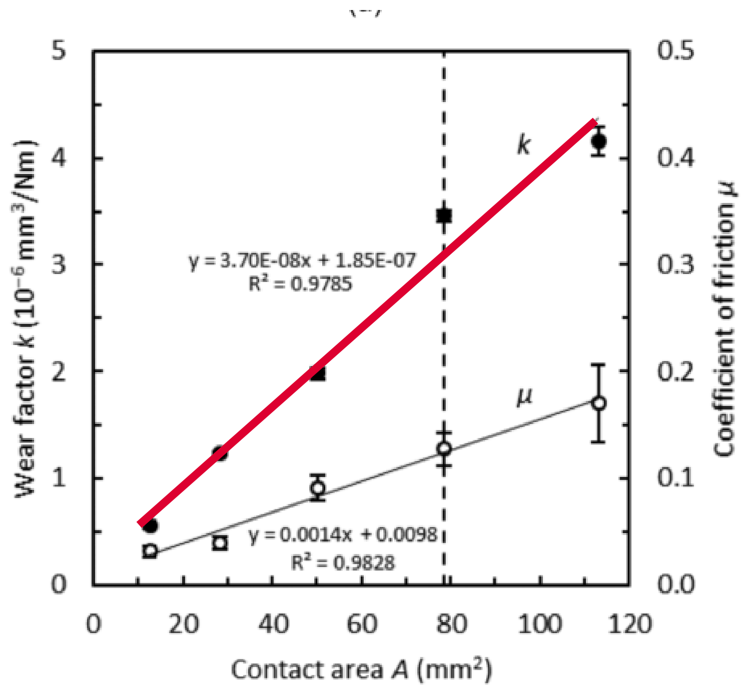


Abduction angle	Plastic deformation (mm^3)	Coefficient of friction	Contact pressure (MPa)	Contact area (mm^2)
60°	23	0.135	17.5	280
45°	15	0.170	11	340
30°	19	0.160	7	390

Ranusa et.al Korduba et.al

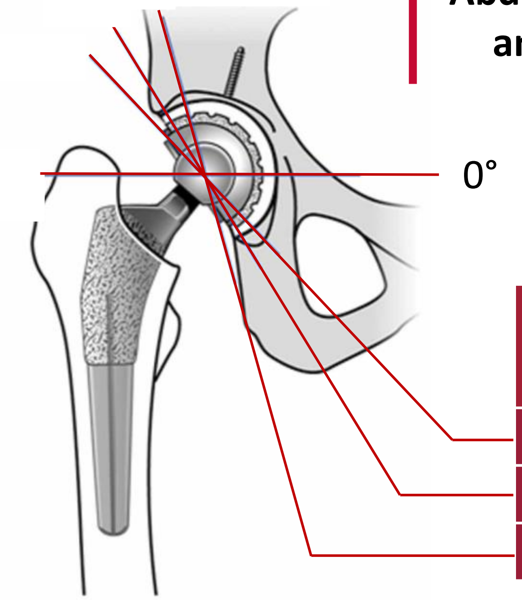
Saikko et al., 2017

Effect of Contact Area on the Wear and Friction of UHMWPE in Circular Translation Pin-on-Disk Tests



Discussion – Wear and Degradation of UHMWPE

↑ **Abduction angle** ↓ Contact area ↑ Contact pressure ↓ **Wear**

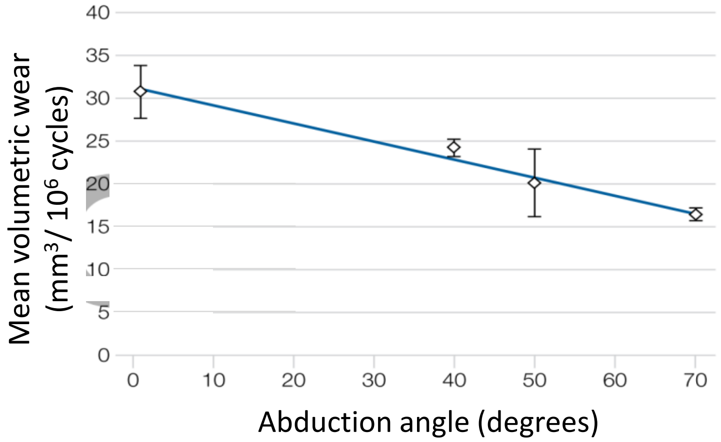


Abduction angle	Plastic deformation (mm^3)	Coefficient of friction	Contact pressure (MPa)	Contact area (mm^2)
60°	23	0.135	17.5	280
45°	15	0.170	11	340
30°	19	0.160	7	390

Ranusa et.al Korduba et.al

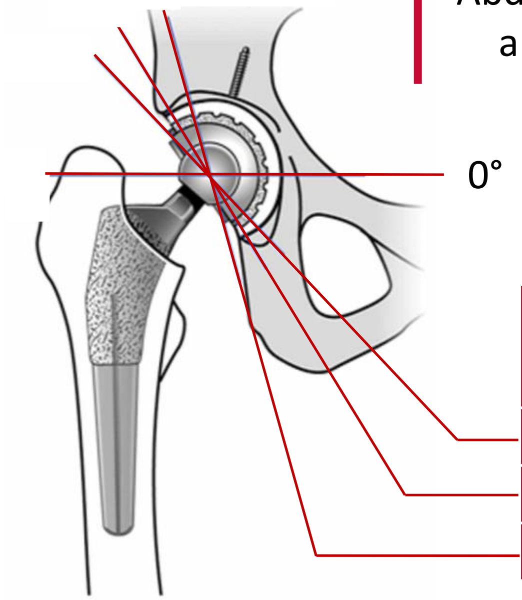
Korduba et al., 2014

FEM analysis, Effect of acetabular cup abduction angle on wear of UHMWPE in hip simulator testing



Discussion – Wear and Degradation of UHMWPE

↑ Abduction angle ↓ **Contact area** ↑ Contact pressure ↓ Wear ↓ **Coefficient of friction**

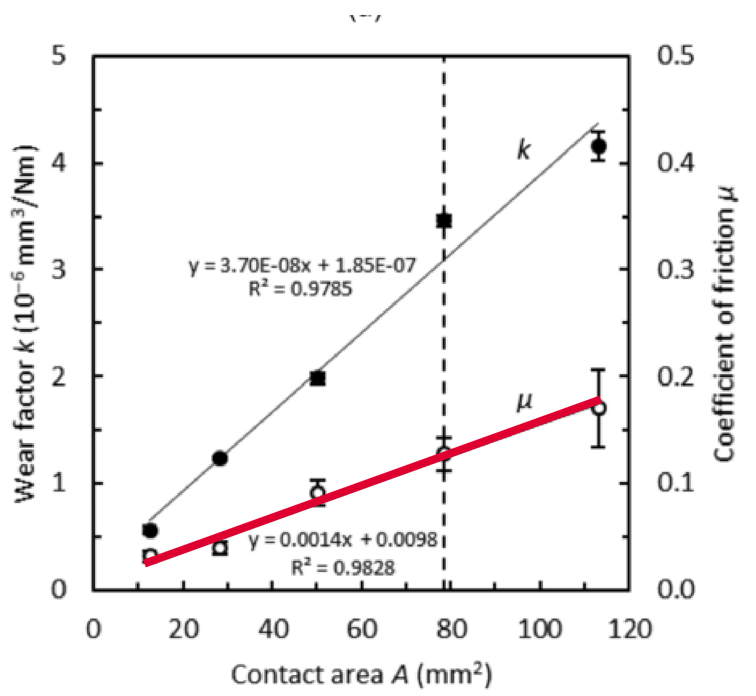


Abduction angle	Plastic deformation (mm^3)	Coefficient of friction	Contact pressure (MPa)	Contact area (mm^2)
60°	23	0.135	17.5	280
45°	15	0.170	11	340
30°	19	0.160	7	390

Ranusa et.al Korduba et.al

Saikko et al., 2017

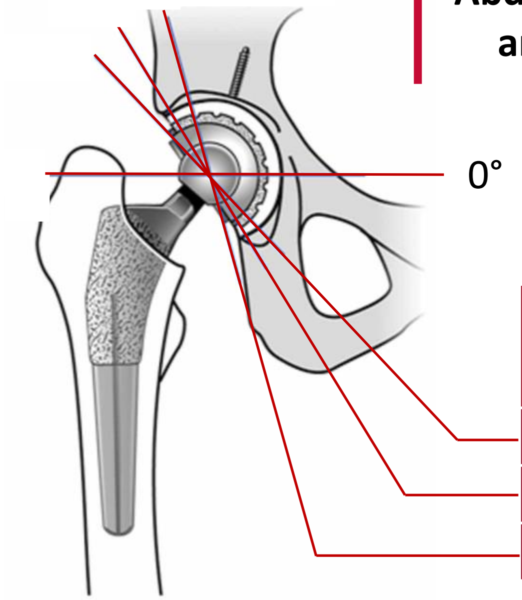
Effect of Contact Area on the Wear and Friction of UHMWPE in Circular Translation Pin-on-Disk Tests



INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN

Discussion – Wear and Degradation of UHMWPE

↑ **Abduction angle** ↓ Contact area ↑ Contact pressure ↓ Wear ↓ **Coefficient of friction**



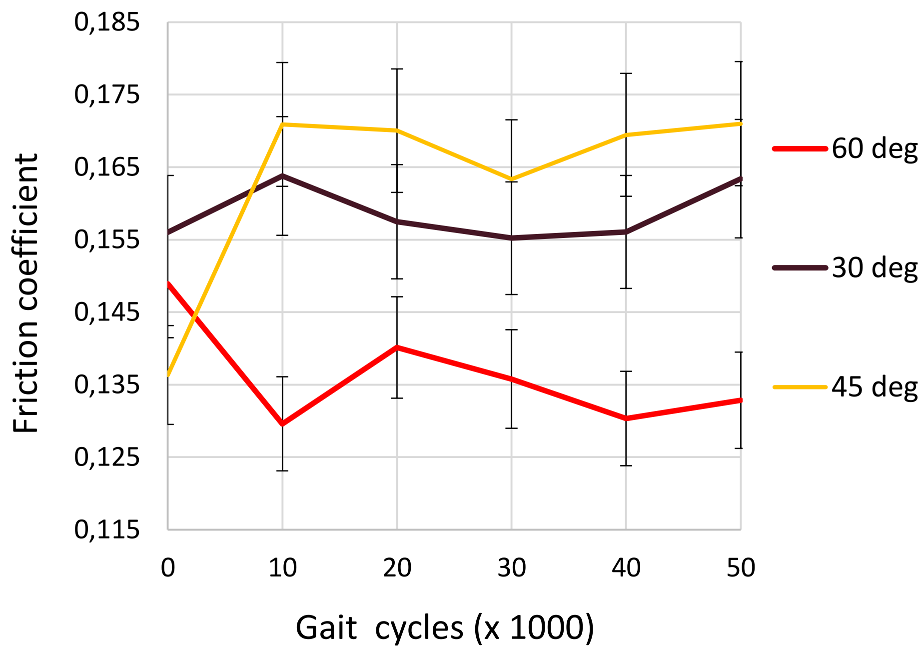
Abduction angle	Plastic deformation (mm^3)	Coefficient of friction	Contact pressure (MPa)	Contact area (mm^2)
60°	23	0.135	17.5	280
45°	15	0.170	11	340
30°	19	0.160	7	390

Ranusa et.al Korduba et.al

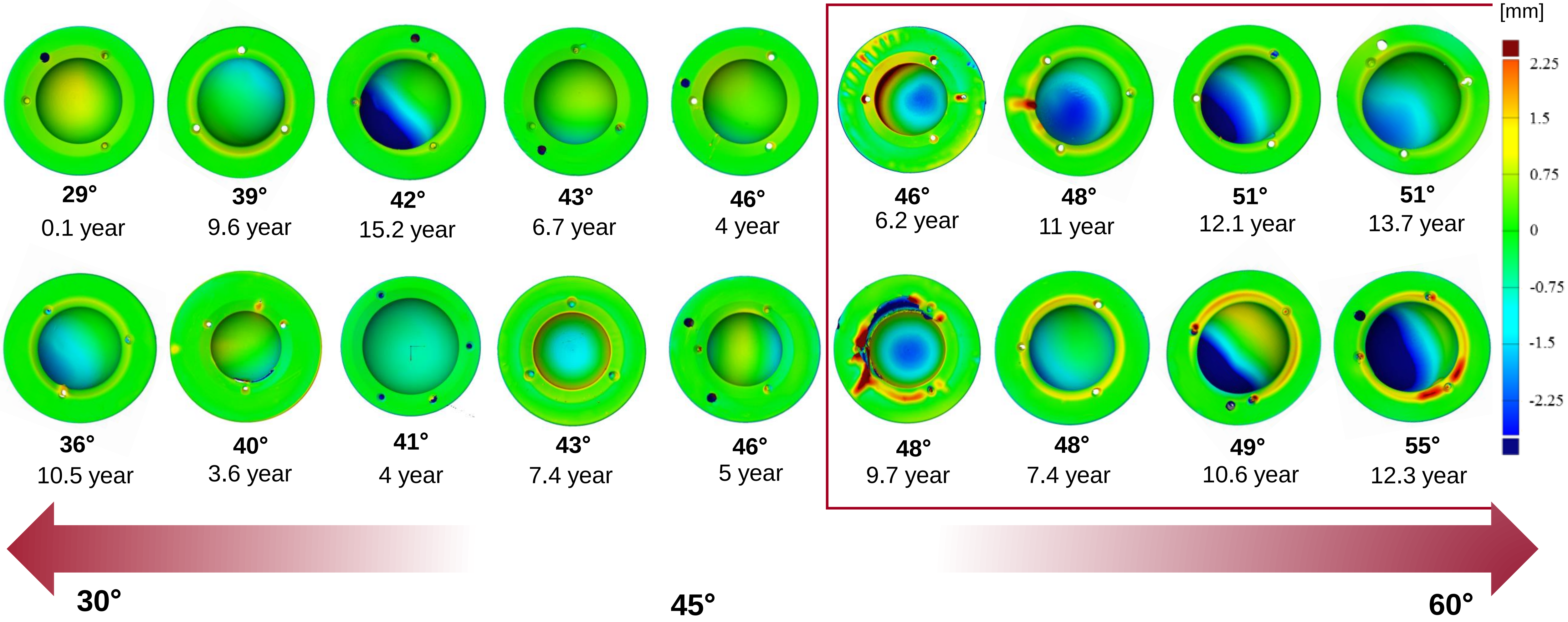
Higher abduction angles are associated with lower wear.

Zeman, Ranuša et al., 2018

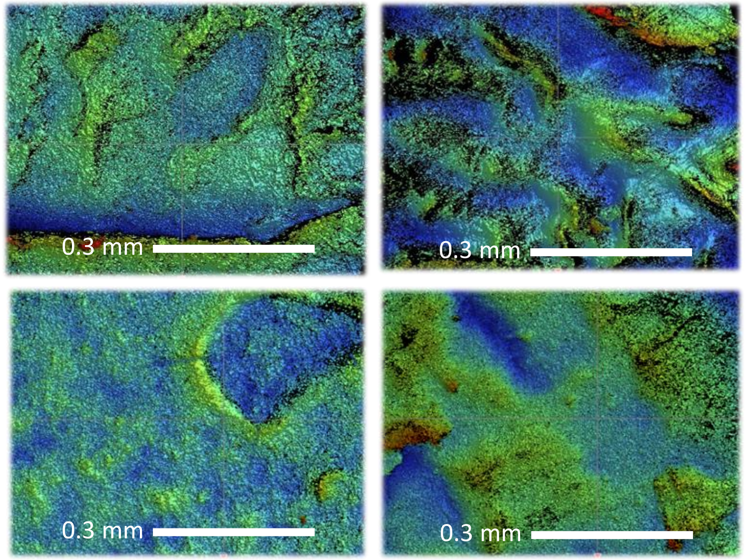
Effect of Contact Area on the Wear and Friction of UHMWPE in Circular Translation Pin-on-Disk Tests



Discussion - Retrievals



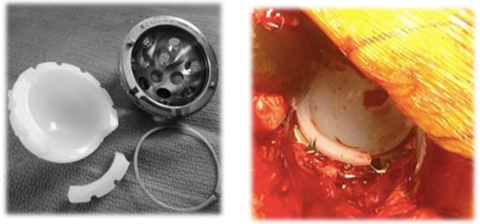
Discussion - Retrievals



Delamination and plastic deformations (0.5 – 2 µm)

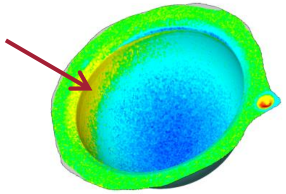
Ranusa et al., 2017

Wear and Roughness of Bearing Surface in Retrieved Polyethylene Bicon-Plus Cups



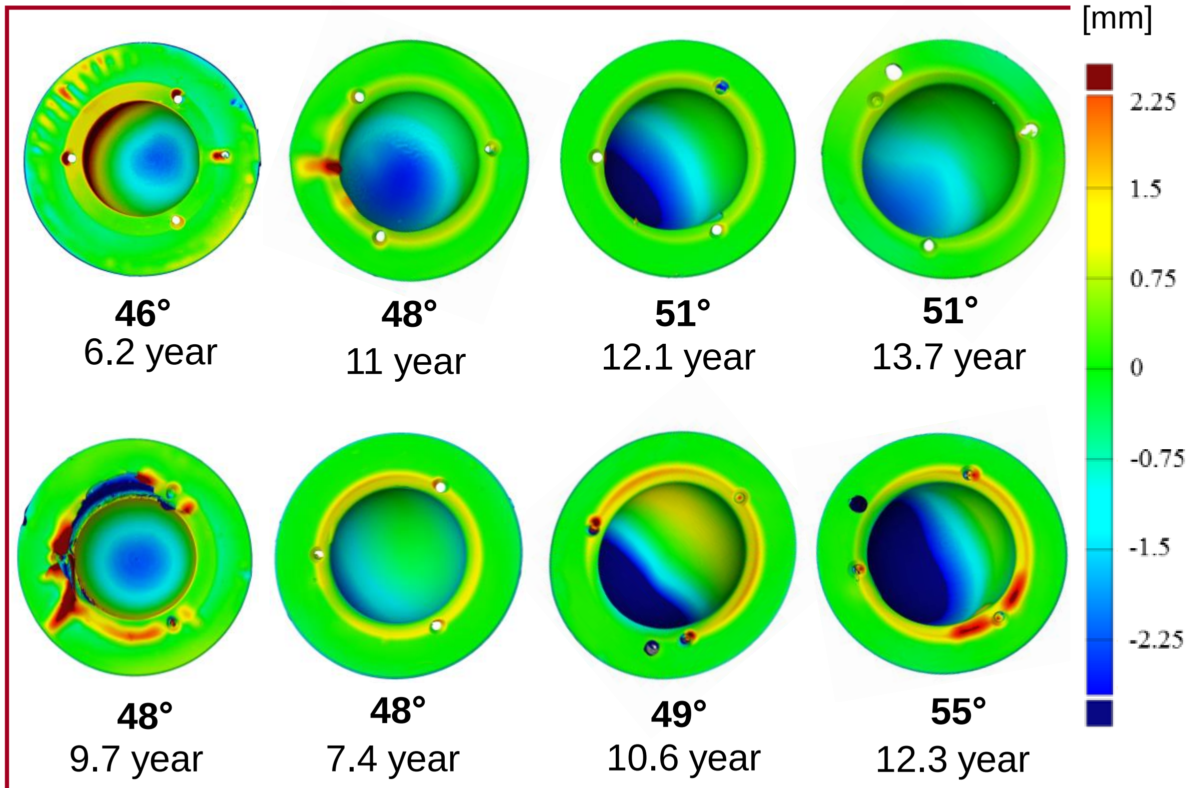
Stephen et al., 2016

Total hip arthroplasty: Techniques and results



Zeman et al., 2018

UHMWPE acetabular cup creep deformation during the run-in phase of THA's life cycle

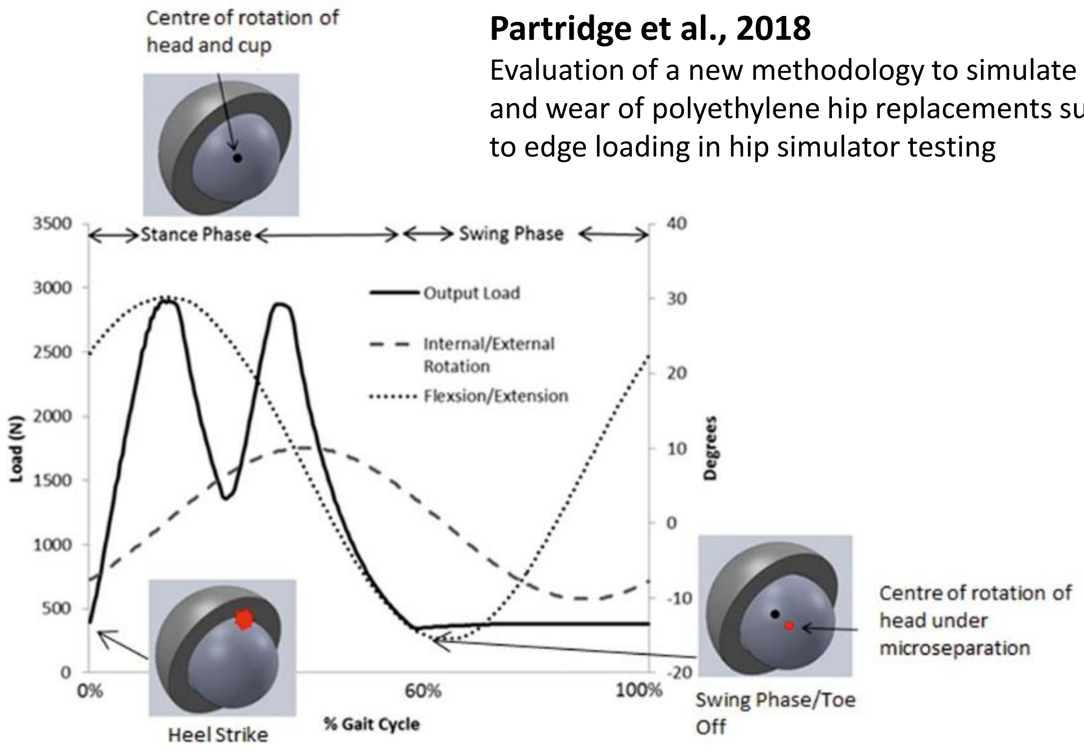


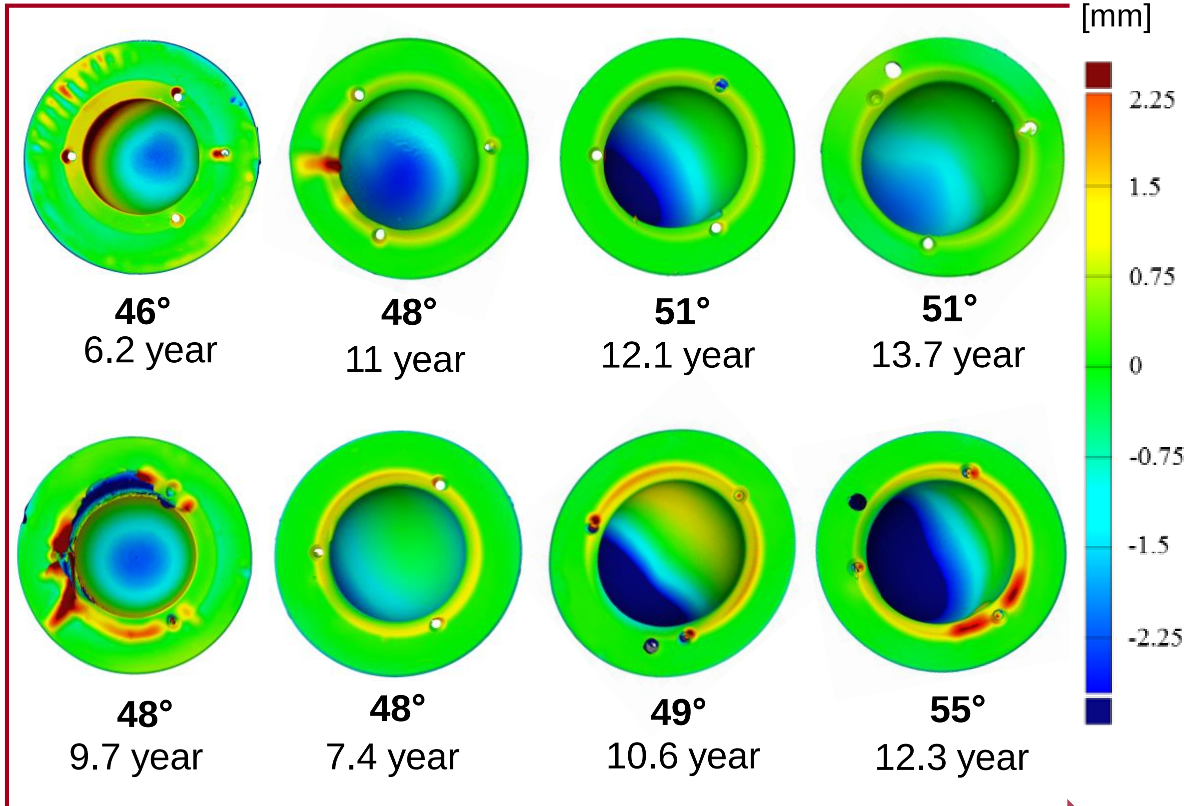
30° 45° 60°

Discussion - Retrievals

Partridge et al., 2018

Evaluation of a new methodology to simulate damage and wear of polyethylene hip replacements subjected to edge loading in hip simulator testing





Higher angles – problem with plastic deformation and edge damages

30° 45° 60°

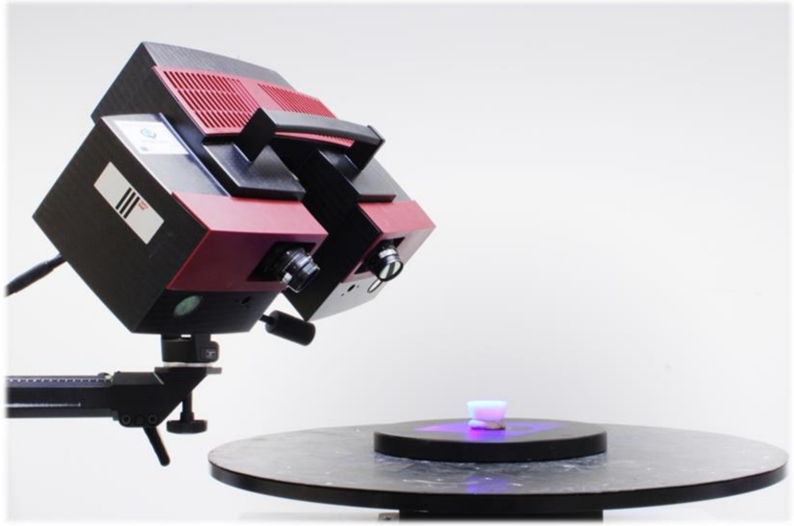
Conclusions

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?

Optical scanning method

- Analysis of volumetric wear
- Standard deviation **5 µm**
- Accuracy of wear determination **up to 10 %** of wear amount
- Contribution of creep **15 – 23 mm^3**
- Contribution of surface roughness up to **2.5 mm^3**
- Influence of manufacturer tolerances



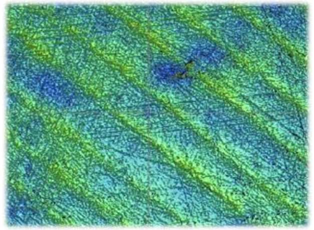
Benefits

- Time efficiency (up to 20 min)
- Analysis of the entire surface (both creep and wear)
- Possibility of damage reconstruction (damages during surgery)
- Possibility to include surface data using topography analysis

Conclusion

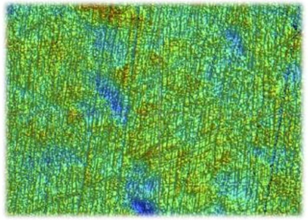
Scientific questions

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



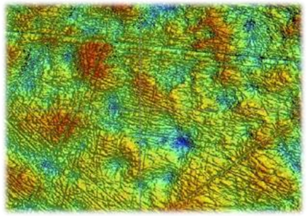
Wear rate

- Surface analysis of 18 extracted UHMWPE liners
- There is no direct connection between survival time and volumetric wear rate

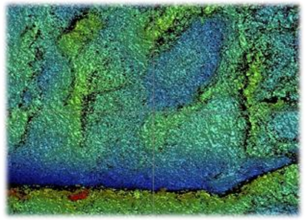


Surface structure

- Significant plastic deformation and delamination were observed in implants with a higher angles



- Typical roughness values and surface topography for different types of wear
    - Delamination, plastic deformations
    - Fatigue, pitting
    - Smoothening, Polishing
    - Unworn areas



INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN

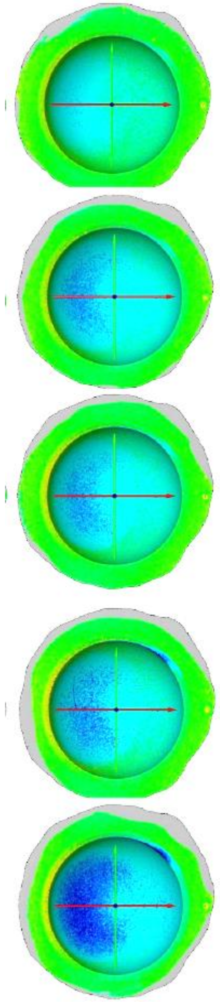
Conclusion

Scientific questions

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

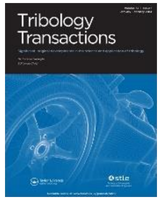
Creep Behaviour

- Contribution of creep **15 – 23 mm^3**
- The lowest plastic deformation at the **45 deg** angle
- The highest plastic deformation at the **60 deg** angle
- Higher angles – rim elevation, cause of fracture



Outcomes of PhD thesis

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.
Author's contribution 80%
Cited by – 10 (Google scholar)
Journal impact factor = 1.723, Quartile Q2, CiteScore = 1.57



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.
Author's contribution 50%
Cited by – 4 (Google scholar)
Journal impact factor = 3.239, Quartile Q1, CiteScore = 3.49

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, 87, 30-39.
Author's contribution 50%
Cited by – 0 (Google scholar)
Journal impact factor = 3.239, Quartile Q1, CiteScore = 3.49

List of Publications

Papers published in journals with impact factor

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.

RANUŠA, M., J. GALLO, M. HOBZA, M. VRBKA, D. NEČAS, and M. HARTL. Wear and Roughness of Bearing Surface in Retrieved Polyethylene Bicon-Plus Cups. *Acta Chirurgiae Orthopaedicae et Traumatologiae Cechoslovaca,* 2017, 84(3), 159–167.

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.

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, 87, 30-39.

List of Publications

Conference abstracts

HOBZA, M. and M. RANUSA. Zhodnocení typu a míry otěru u extrahovaných jamek Bicon. XXIII. Mezinárodní sympozium FREJKOVY DNY, 2015, Brno, Czech Republic.

RANUSA, M., M. VRBKA, I. KŘUPKA and M. HARTL. M. Development and Validation of an Optical Scanning Method for Volumetric Wear Analysis. *The 17th Nordic Symposium on Tribology - NORDTRIB 2016*, 2016, Hämeenlinna, Finland.

RANUSA, M., M. VRBKA, J. GALLO, I. KŘUPKA and M. HARTL. Influence of acetabular cup inclination on wear of UHMWPE liner. 6th *World Tribology Congress (WTC)*, 2017, Beijing, China.

RANUSA, M., M. VRBKA, J. GALLO, I. KŘUPKA and M. HARTL. Influence of Positioning Retrieved Acetabular Liners in Vivo on the Wear Rate Determined by optical scanning. 2th Czech-Japan Tribology Workshop, 2017, Takamatsu, Japan

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.

Thank you for attention.

Matus.Ranusa@vut.cz

INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN