Patterned microtexture to reduce polyethylene wear in metal-on-polyethylene bearings, with application in prosthetic hip implants

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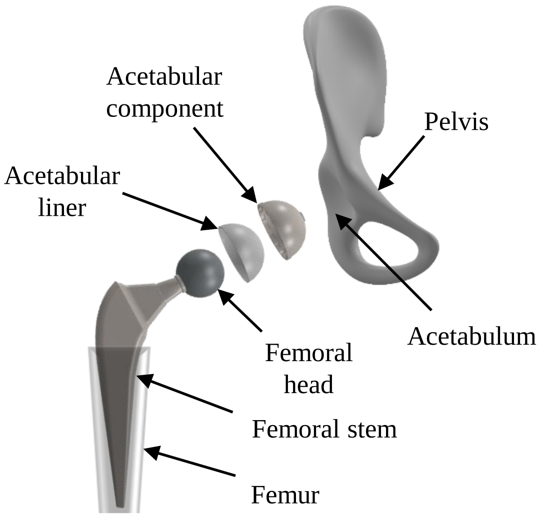
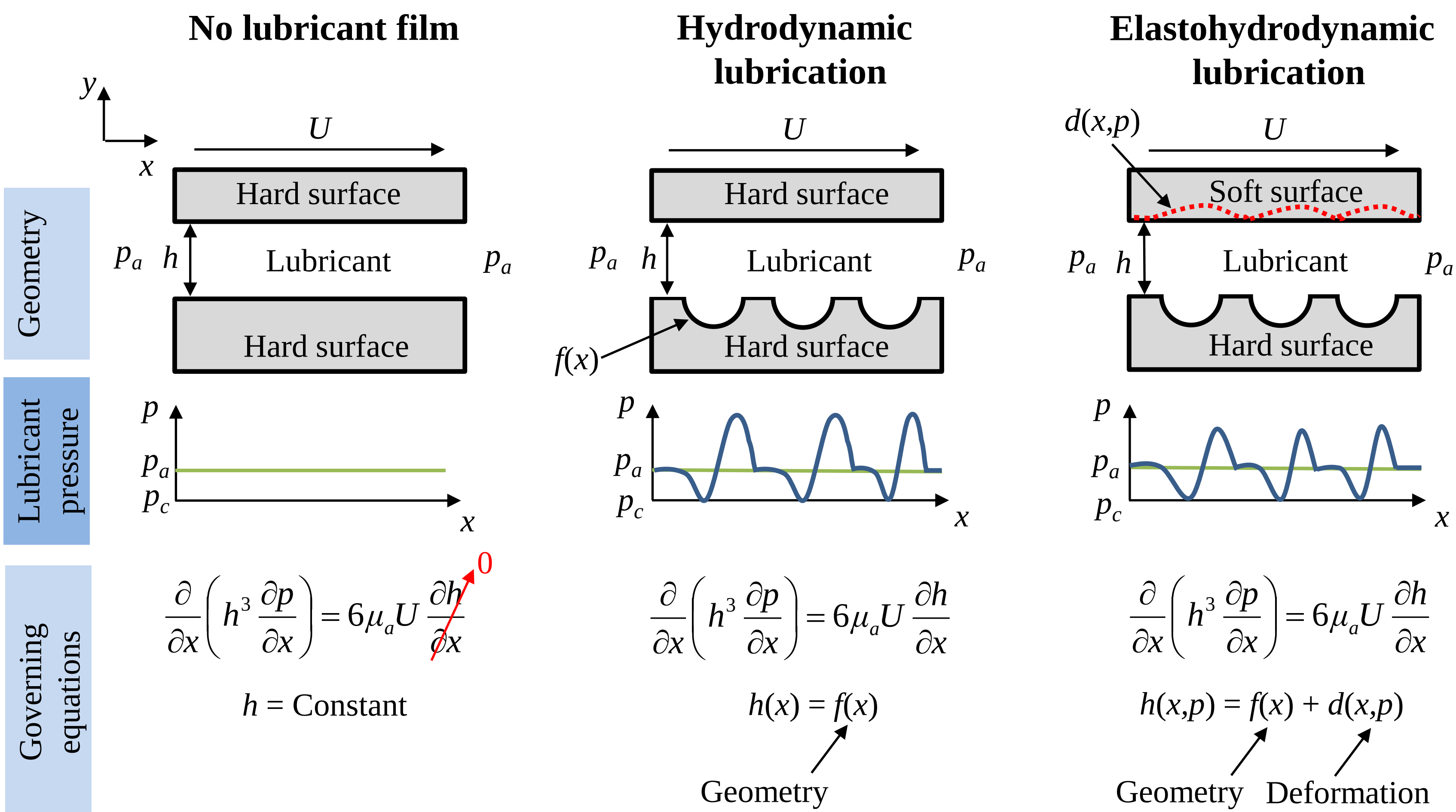
Introduction (1)

- The most common type of prosthetic hip implant in the United States is a metal-on-polyethylene (MoP) prosthetic hip implant.
  - A metal femoral head implanted in the femur articulates with a polyethylene acetabular liner implanted in the pelvis to replace the natural hip joint function.
  - Statistical survivorship of MoP prosthetic hip implants declines significantly after 15-20 years of use.
  - Adverse immunological reaction to polyethylene wear particles may lead to mechanical instability of the implant, causing the need for revision surgery.
- **Critical problem**
  - Longevity of MoP prosthetic hip implants.
- **Proposed solution**
  - Reduce polyethylene wear by adding a patterned microtexture to the femoral head, which induces elastohydrodynamic lubrication during a portion of the gait cycle.



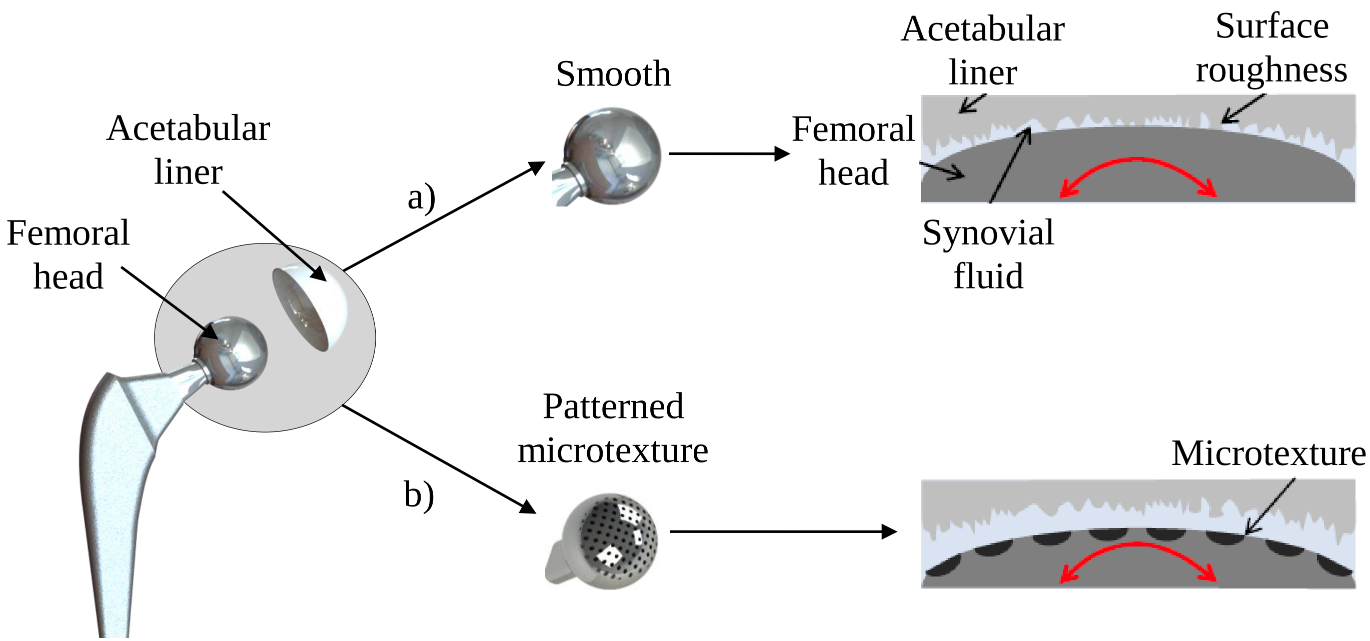
Introduction (2)

- Relevant lubrication mechanisms:



Introduction (3)

- Sliding interface between acetabular liner and:
  a) Smooth femoral head.
  b) Patterned microtextured femoral head.



- Patterned microtexture creates microhydrodynamic bearings that increase the lubricant film thickness (for constant bearing load).

Research objective

- The **research objectives** are:

1. To test the hypothesis that a patterned microtexture manufactured on a CoCrMo bearing surface, articulating with a smooth polyethylene bearing surface, increases the lubricant film thickness between both bearing surfaces, and reduces polyethylene wear, compared to a non-textured, smooth CoCrMo bearing surface.

2. To quantify the effect of patterned microtexture design parameters and bearing operating conditions on the lubrication regime, lubricant film thickness, and the friction coefficient between both bearing surfaces and its correlation with polyethylene wear.

3. To implement machine learning methods on available pin-on-disc polyethylene wear datasets in the literature and derive a data-driven model of polyethylene wear to supplement wear experiments.

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- Background review
- Simulation of microtextured surface lubrication
- Instrumentation and materials
  - Design and implementation of pin-on-disc testers
  - Manufacturing CoCrMo discs and polyethylene pins
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  - Wear experiments of polyethylene pins against CoCrMo discs
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Background (1)

- More than 450,000 total hip replacement (THR) surgeries are performed in the United States each year (2014 data) [1].
  - Different bearing types exist, MoP is the most common one.

Source: [2]

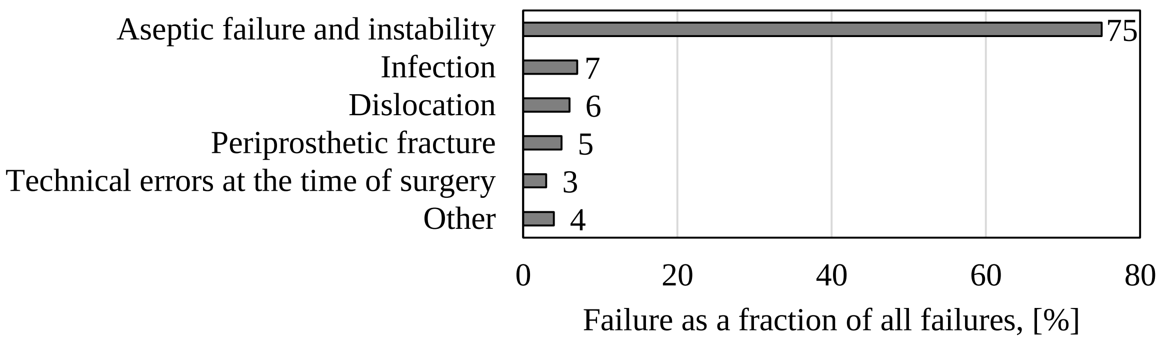
MoP

Metal-on-metal

Ceramic-on-ceramic

Ceramic-on-polyethylene

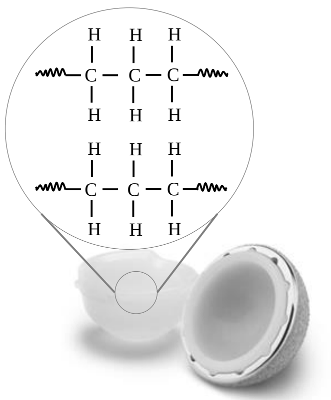
- Most common reasons for THR to fail [3]:



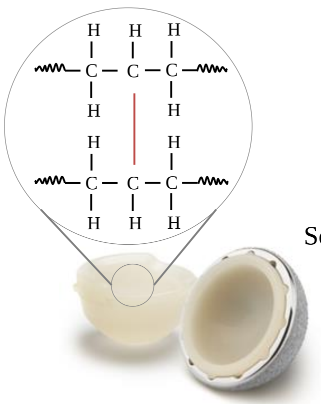
[1] Heckmann ND, Sivasundaram L, Stefl MD, Kang HP, Basler ET, Lieberman JR. J Arthroplasty 2018;33:1757–1763.e1.
[2] http://www.orthonik.com.ua/en/company/partners. [3] Holt G, Murnaghan C, Reilly J, Meek RM..Clin Orthop Relat Res. 2007;460:240-252.

Background (2)

- Research to increase longevity of prosthetic hip implants can be categorized as:
  1. Improving the mechanical properties of the polyethylene liner:
     - Highly cross-linked polyethylene (HXPE).
     - Addition of antioxidant materials such as vitamin-E to HXPE.



Polyethylene



HXPE

Source: [1]

  2. Improving the design of the femoral head/liner pairs:
     - New materials, such as zirconia, silicon nitride, and tungsten.
     - Manufacturing ultra-smooth bearing surfaces.

Ultra-smooth bearing surfaces

Source: [2]

[1] https://www.coringroup.com/us/news/ecima-gains-fda-clearance1/.
[2] https://www.nextsteparthropedix.com/hip-replacement

Background (3)

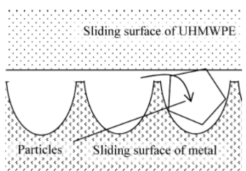
- **Previous attempts** to reduce friction and wear in MoP prosthetic hip implants by employing surface microtexturing compared to using a smooth surface:

Polyethylene wear reduction
Friction coefficient reduction

69%
36.2%

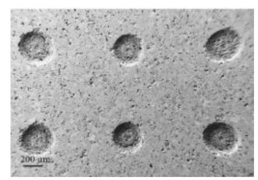
Source: [1]

61%



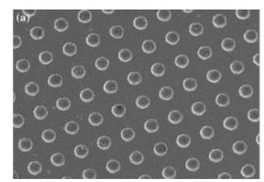
Source: [2]

53%
22%



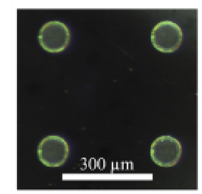
Source: [3]

25%



Source: [4]

Reduced friction over almost the entire kinematic cycle



Source: [5]

- **Limitations:**
  - Unrealistic testing conditions and materials.
  - Lack of understanding of how microtexture reduces polyethylene friction and wear.
  - No systematic study is available that quantifies the polyethylene wear rate and friction coefficient as a function of microtexture design parameters and operating conditions.

[1] H. Ito, K. Kaneda, T. Yuhta, I. Nishimura, K. Yasuda, and T. Matsuno, *J. Arthroplasty*, vol. 15, no. 3, pp. 332–338, Apr. 2000.
[2] H. Sawano, S. Warisawa, and S. Ishihara, *Precis. Eng.*, vol. 33, no. 4, pp. 492–498, Oct. 2009.
[3] T. Roy, D. Choudhury, S. Ghosh, A. Bin Mamat, and B. Pingguan-Murphy, Ceram. Int., vol. 41, no. 1, pp. 681–690, Jan. 2015.
[4] M. Cho and H.J. Choi, Tribol. Lett., vol. 56, no. 3, pp. 409–422, Dec. 2014.
[5] A. Chyr, M. Qiu, J. W. Speltz, R. L. Jacobsen, A. P. Sanders, and B. Raeymaekers, Wear, vol. 315, no. 1–2, pp. 51–57, Jul. 2014.

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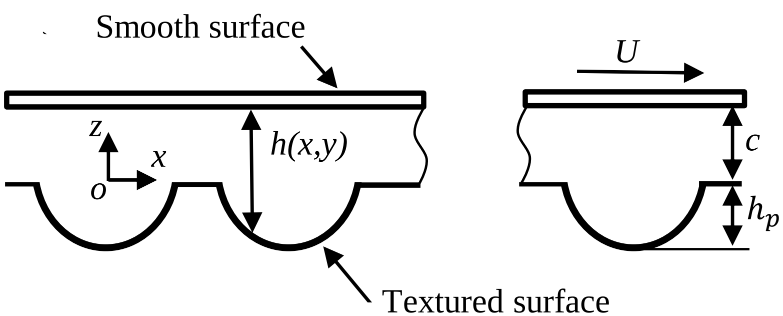
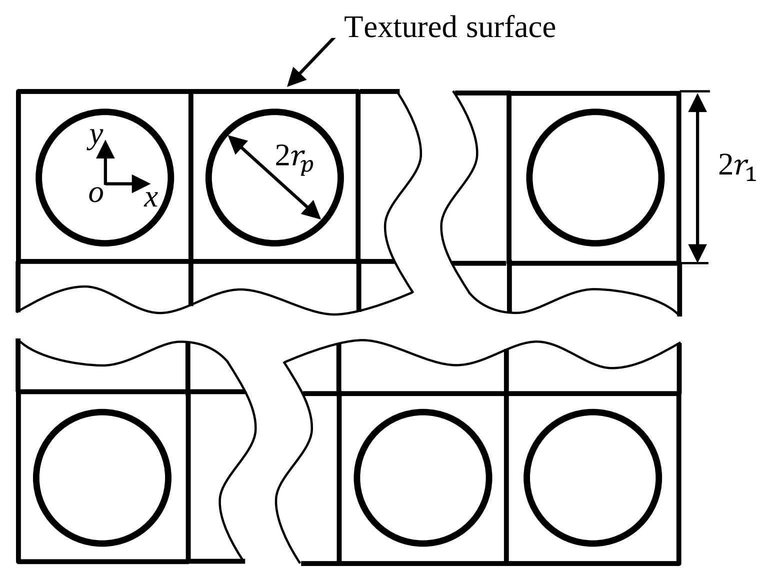
Simulation of microtextured surface lubrication (1)

- Numerical simulation of the lubricant film thickness between the acetabular liner and a microtextured femoral head of a MoP prosthetic hip implant.
  - This work has been accomplished by another PhD student in our research group [1].

- The patterned microtexture is fully described by:
  - The texture aspect ratio $\varepsilon = h_p/2r_p$
  - The texture density $S_p = \pi r_p^2/(4r_1^2)$





Department of Mechanical Engineering
COLLEGE OF ENGINEERING | THE UNIVERSITY OF UTAH

[1] M. Qiu, A. Chyr, A. P. Sanders, and B. Raeymaekers, *Tribol. Int.*, vol. 77, pp. 106–110, Sep. 2014

Simulation of microtextured surface lubrication (2)

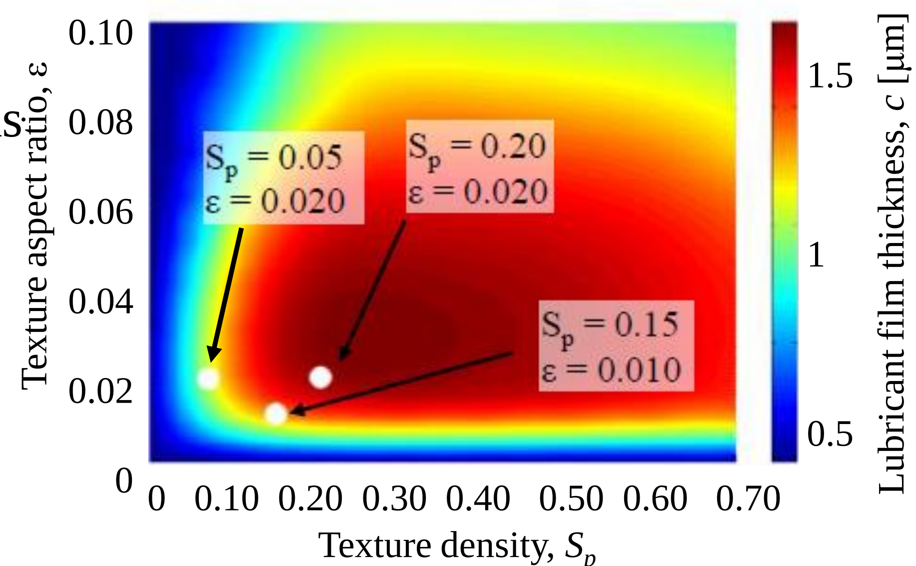
- The simulation involves simultaneous solution of three equations:
  1. Two-dimensional, incompressible Reynolds equation (relates pressure to spacing):

$$\frac{\partial}{\partial x}\left(h^3 \frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(h^3 \frac{\partial p}{\partial y}\right)=6\mu_a U \frac{\partial h}{\partial x}$$

  2. Elastic deformation of the polyethylene surface resulting from local pressure.
  3. Load-carrying capacity resulting from the bearing pressure must balance the external bearing load.

- The lubricant film thickness depends on the patterned microtexture design, an optimum exists.

- Indicate several microtexture designs that we use in our experiments.



Source: [1]

[1] M. Qiu, A. Chyr, A. P. Sanders, and B. Raeymaekers, *Tribol. Int.*, vol. 77, pp. 106–110, Sep. 2014

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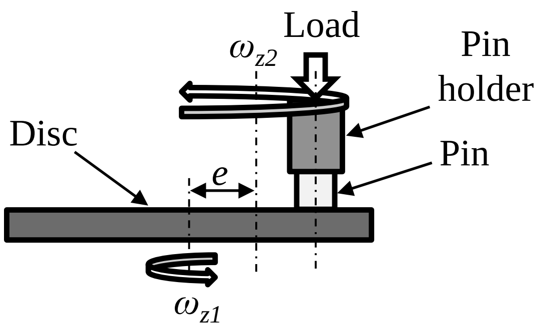
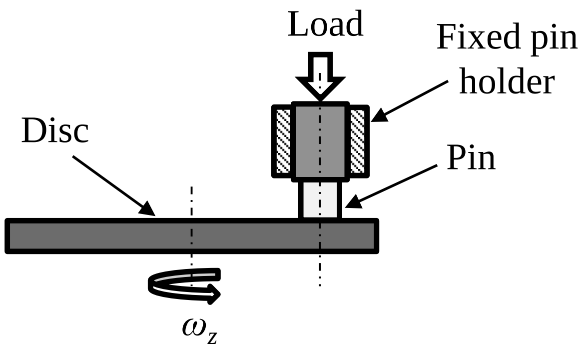
Design and implementation of two pin-on-disc testers

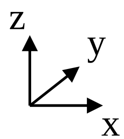
- Pin-on-Disc (PoD) testers are a class of tribotesters in which a pin is mechanically loaded against a disc, while relative motion between them, creates friction and wear.

1. Single station PoD tester to measure friction and wear.



2. Five-station PoD tester to parallelize wear data-collection.

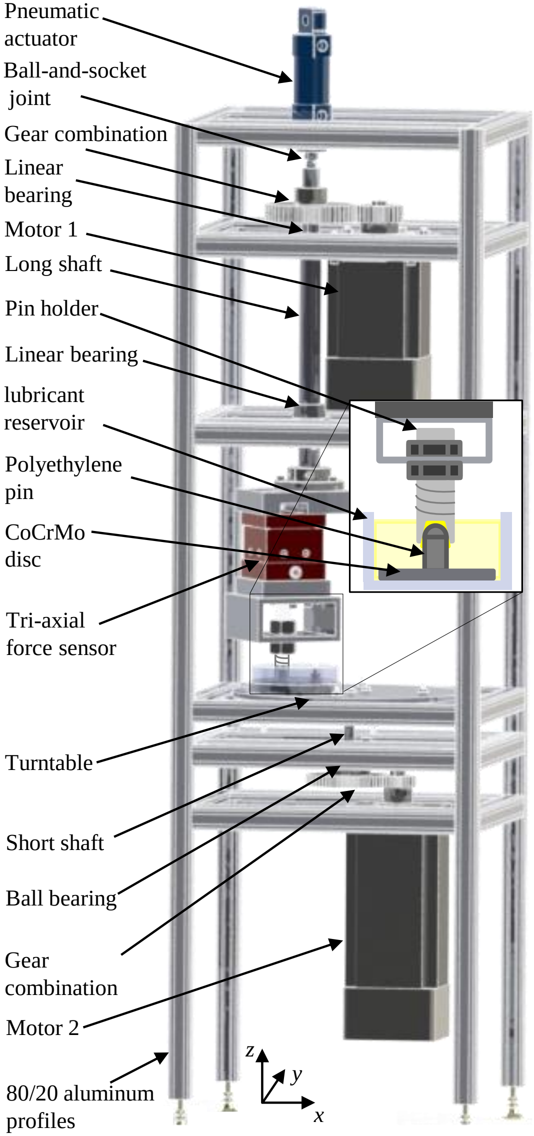




Single-station PoD tester (1)

- Capabilities:
  1. User-specified wear track (any 2D shape within the operating envelope).
  2. Static/dynamic contact pressure.
  3. Measure friction force.
  4. Measure wear.

- Three parts:
  1. The motion mechanism.
  2. The contact pressure mechanism.
  3. The frame.

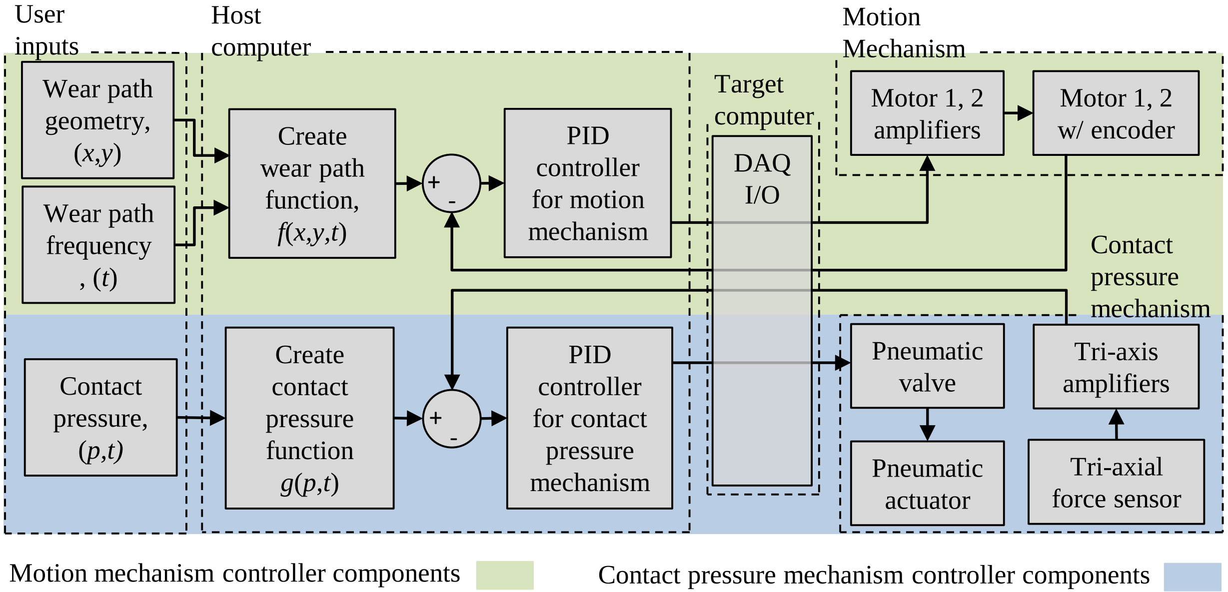


Single-station PoD tester (2)

- A host-target computer system manages the PoD tester in real-time using Matlab xPC target™.
- A PID controller performs closed-loop motion control, using position feedback from the encoders.
- A PID controller performs closed-loop contact pressure control, using the *z*-component of a tri-axial force sensor feedback.

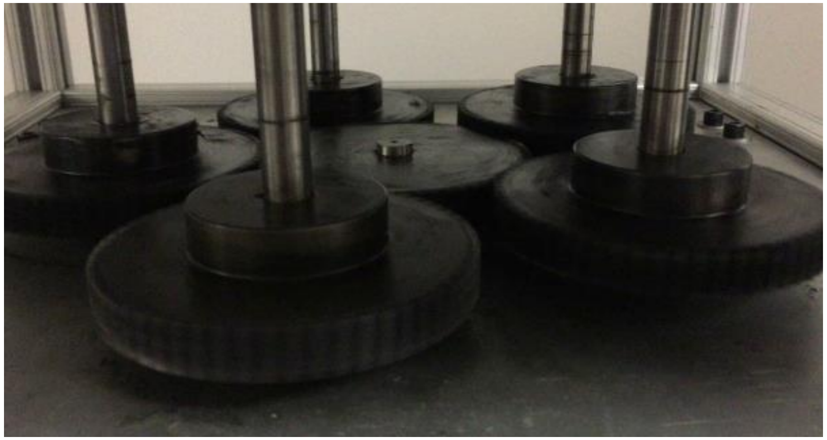
DAQ system

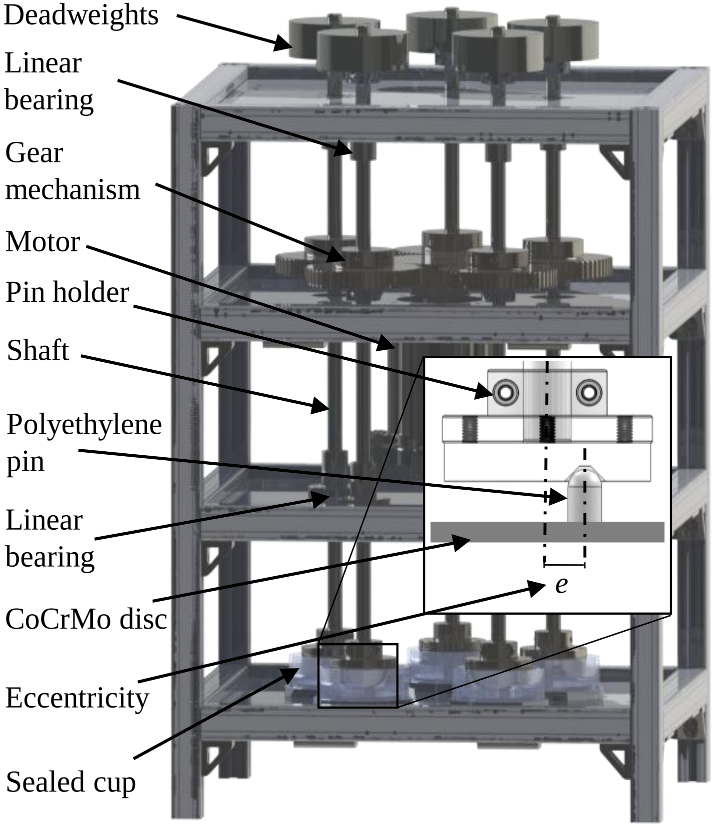
System schematic



Five-station PoD tester

- Five-station PoD tester to parallelize wear data collection.
- Polyethylene is viscoelastic and, thus, wear experiments cannot be accelerated.
- This PoD tester only follows a circular wear path and applies static loading.

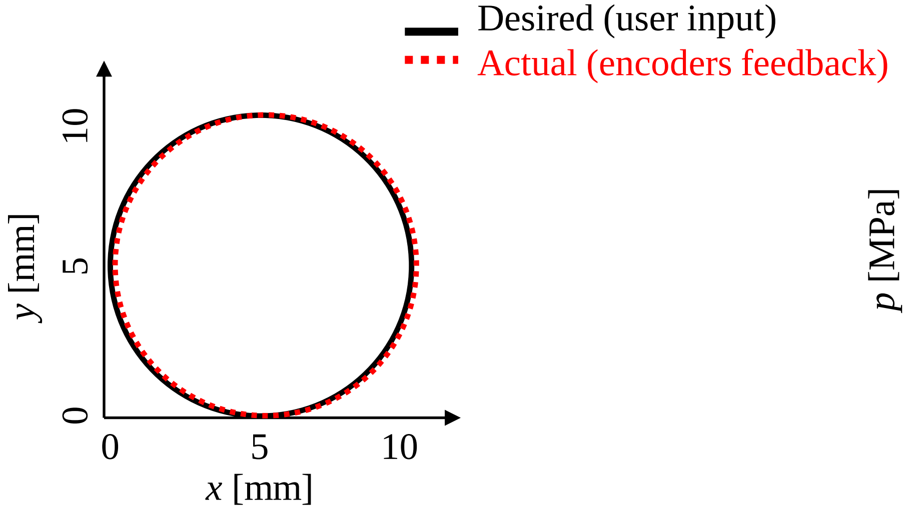




Validating PoD tester performance

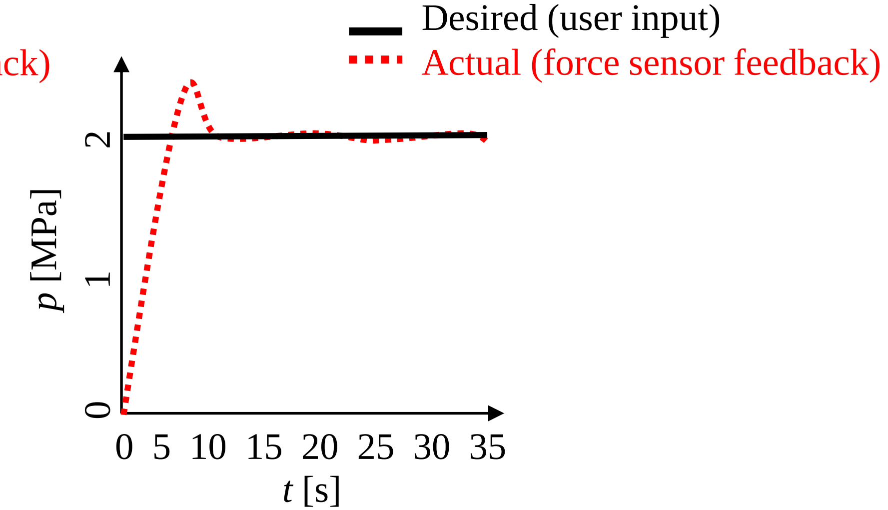
- Single-station PoD tester performance:

Wear path (*x*,*y*) tracking



Average tracking error for 60 cycles after 10 seconds < **5%**

Contact pressure (*p*) tracking



Average tracking error for 60 cycles after 10 seconds < **2%**

- Five-station PoD tester performance:
  - The wear path is mechanically defined. Velocity tracking error is **< 1%** for 60 cycles after 10 seconds.
  - We use deadweight for generating contact pressure so there is no tracking error.

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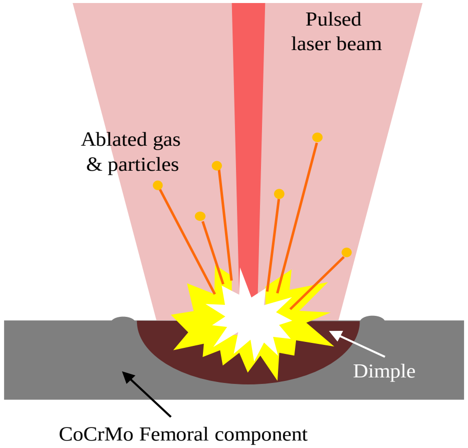
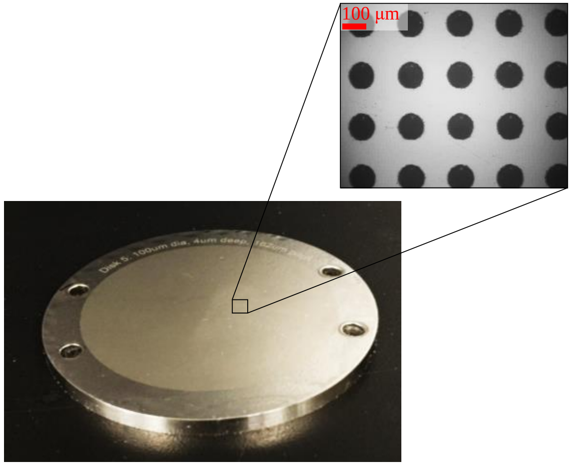
Manufacturing CoCrMo discs and polyethylene pins

- Disc and pin specimens of the same materials that are used in commercial MoP prosthetic hip implants.
- Laser surface texturing with a picosecond laser ablation process to manufacture patterned microtexture designs on smooth CoCrMo (ASTMF1537-08 [1]) discs polished to Ra < 50 nm.



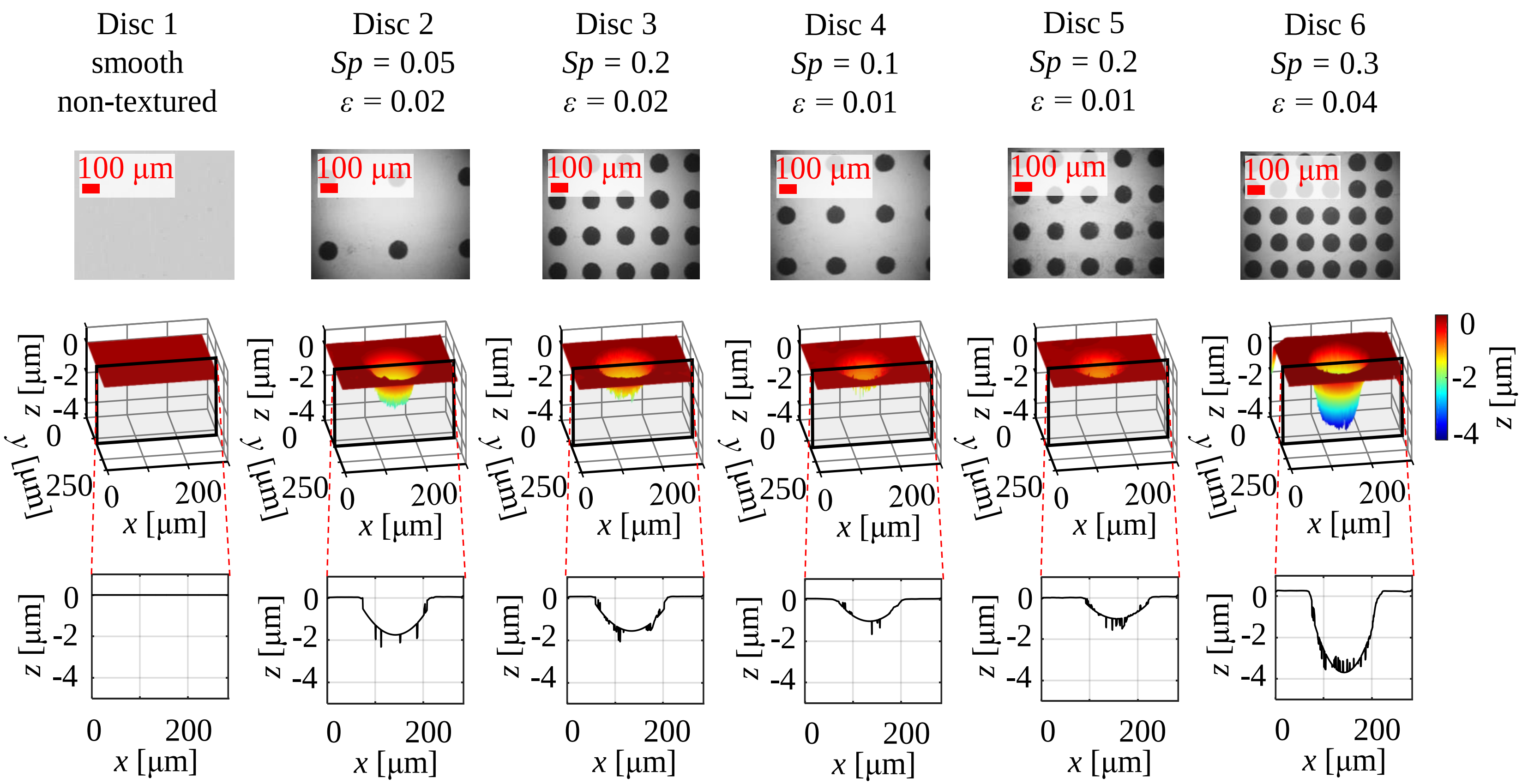


- The surface quality is identical to that of femoral heads of commercial MoP prosthetic hip implant.

[1] ASTM F1537-08 standard specification for wrought cobalt-28chromium-6molybdenum alloys for surgical implants

CoCrMo discs surface analysis

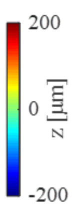
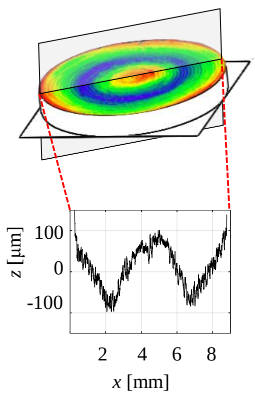
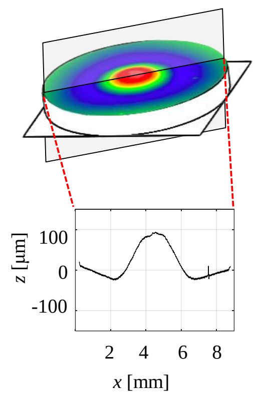
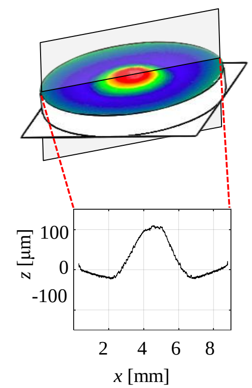
- Five different patterned microtexture designs, selected based on our previous numerical optimization work [1]:



[1] M. Qiu, A. Chyr, A. P. Sanders, and B. Raeymaekers, Tribol. Int., vol. 77, pp. 106–110, Sep. 2014.

Polyethylene pin surface analysis

- Three types of medical grade polyethylene pins:

Pin-type	UHMWPE GUR 1050 [1]	HXPE [1]	VEXPE [2]
Photo			
 White light interferometry			
R_a [μm]	1.312	0.869	0.874
n_s [1/μm^2]	0.491	0.098	0.112
σ_s [μm]	1.265	0.909	0.934
R_s [μm]	0.277	0.732	0.440

[1] ASTM F648-14, astm.org [2]ASTM F2695-12, astm.org

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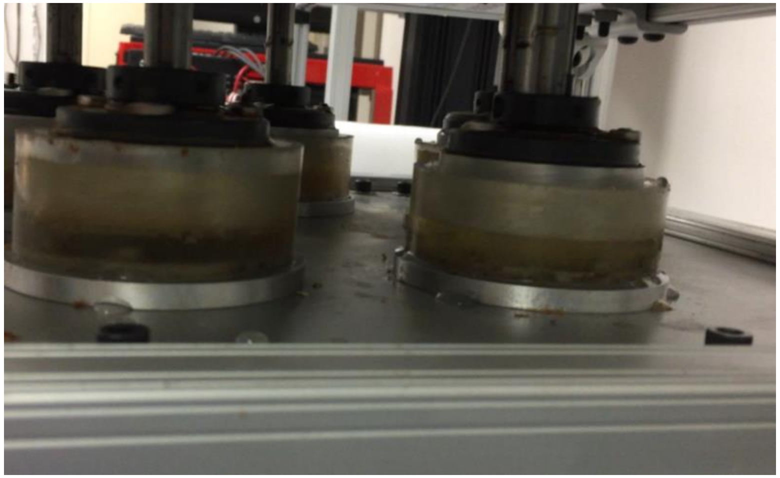
Wear experiments of polyethylene pins against CoCrMo discs

- Polyethylene pins articulating with smooth and microtextured CoCrMo discs.

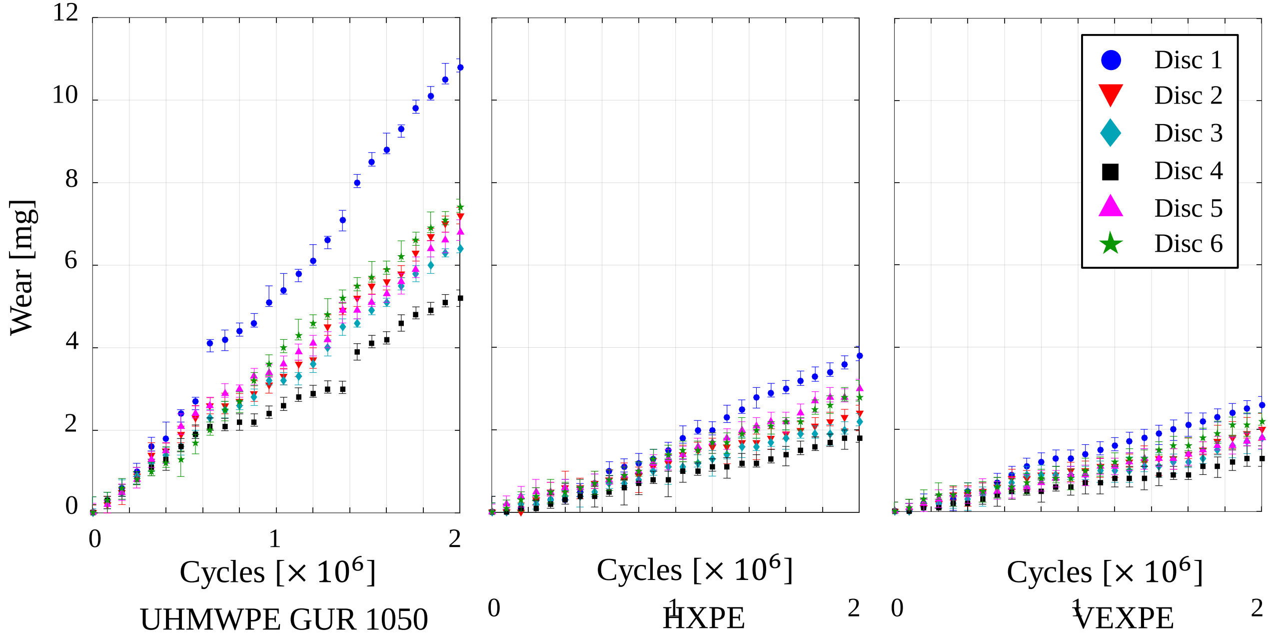


  - Based on the ASTM F732 [1] standard:
    - Two million wear cycles with a circular (*d* =10 mm) wear path.
    - 1 Hz frequency to approximate the frequency of human walking gait.
    - Contact area of 63.6 mm^2 and contact pressure of 2.0 MPa.
    - Bovine serum with 20 mg/ml protein concentration as lubricant.

[1] ASTM F732-00(2011) astm.org

Polyethylene wear analysis (1)

- Gravimetric polyethylene wear measurement in accordance with ASTM F2025 [1], measuring polyethylene wear at 80,000 cycle intervals.

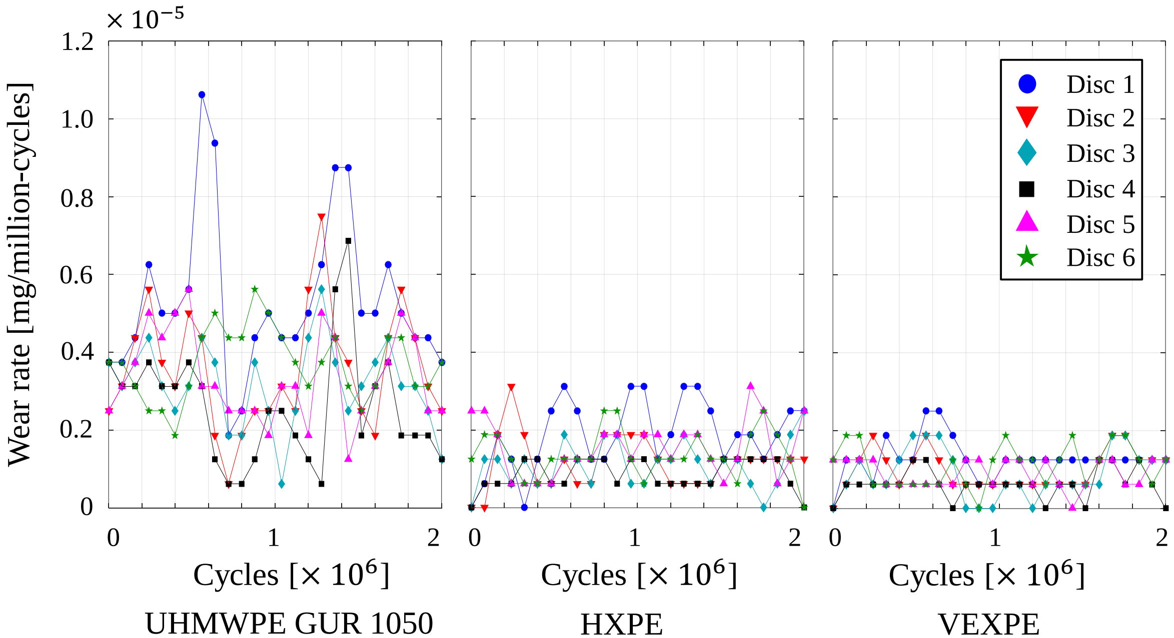


  - The smooth disc always results in higher polyethylene wear than the microtextured discs, independent of the polyethylene type.
  - Wear is dependent on polyethylene type, as expected.

[1] ASTM F2025-06(2012) astm.org

Polyethylene wear analysis (2)

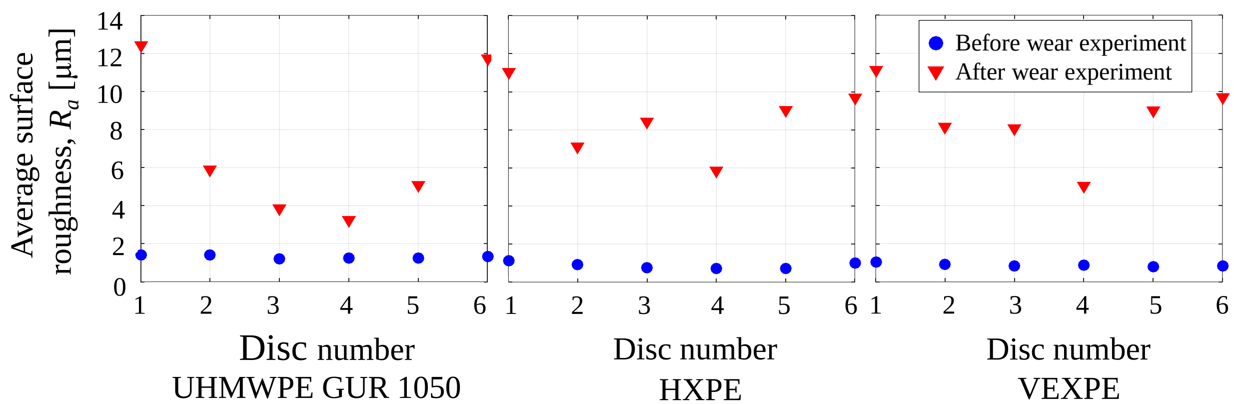
- Polyethylene wear rate calculated from polyethylene wear measurements.



  - High polyethylene wear rate occurs until approximately 600,000 cycles, likely due to machining marks or surface roughness peaks on the articulating surface of the polyethylene pin being removed.
  - Wear rate of UHMWPE GUR 1050 increases after approximately 1.4 million wear cycles, likely due to the fatigue wear.

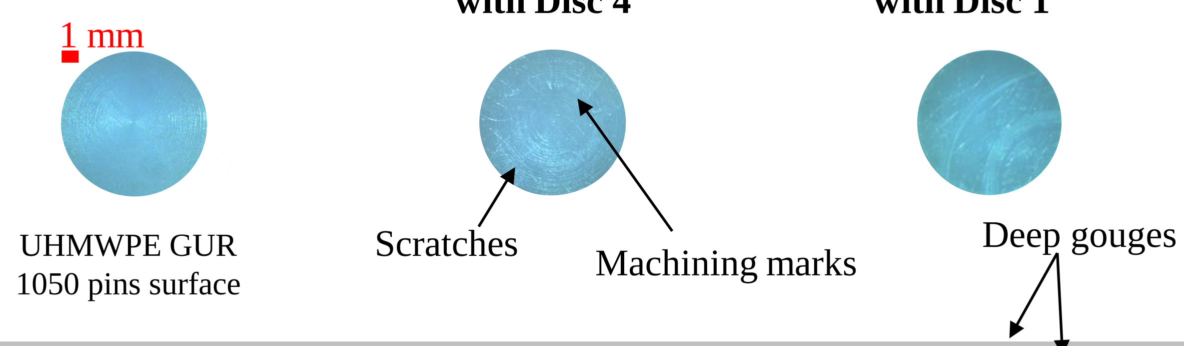
Polyethylene wear analysis (3)

- Surface topography of the polyethylene pins:



  – Polyethylene pin articulating with the smooth CoCrMo disc (Disc 1) always has the highest R_a after wear experiment independent of the material.

Before wear experiment | **After wear experiment with Disc 4** | **After wear experiment with Disc 1**



Conclusions of wear measurements

- The smooth disc always results in higher polyethylene wear than the microtextured discs, independent of the polyethylene type.

- Microtexture creates microhydrodynamic bearings, which reduces contact by increasing the lubricant film thickness between both bearing surfaces, which in turn reduces polyethylene wear.

- Disc 4 ($S_p = 0.1$, $\varepsilon = 0.01$) consistently yields the lowest polyethylene wear, in agreement with the numerical simulation.

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Friction experiments of polyethylene pins against CoCrMo discs (1)

- Human hip kinematics and loading are a function of [1]:
  - Age.
  - Gender.
  - Body mass.
  - Activity level.

Source: [2]

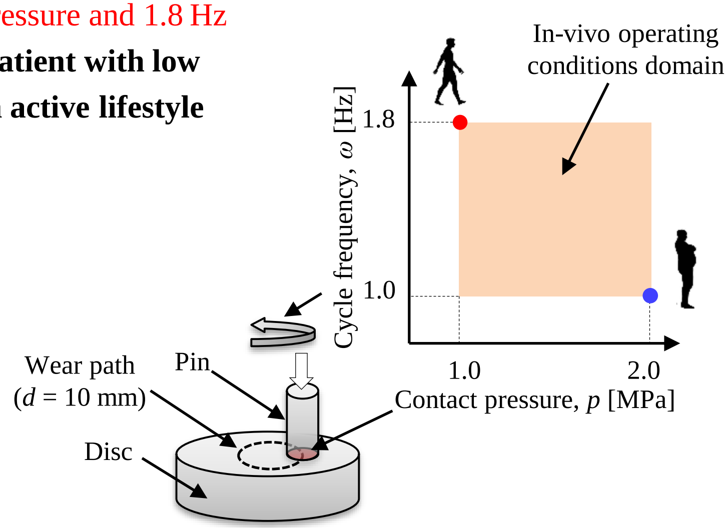
- Quantifying the effect of operating condition on the friction coefficient between polyethylene and microtextured CoCrMo specimens, and the corresponding polyethylene wear rate, is crucial to the design of microtextured prosthetic hip implants, and could eventually allow for patient-specific design.

[1] J. E. Himann, D. A. Cunningham, P. A. Rechnitzer, and D. H. Paterson, vol. 20, no. 2, pp. 161–6, Apr. 1988.
[2] https://www.shutterstock.com/?kw=shutterstock&gclid

Friction experiments of polyethylene pins against CoCrMo discs (2)

- Operating conditions of friction experiments are based on in-vivo operating conditions of prosthetic hip implants, spanning two extreme patients.

1.0 MPa contact pressure and 1.8 Hz cycle frequency: **patient with low body mass and an active lifestyle** (high *S*)



2.0 MPa contact pressure, and 1.0 Hz cycle frequency: **obese patient with a sedentary lifestyle** (low *S*)

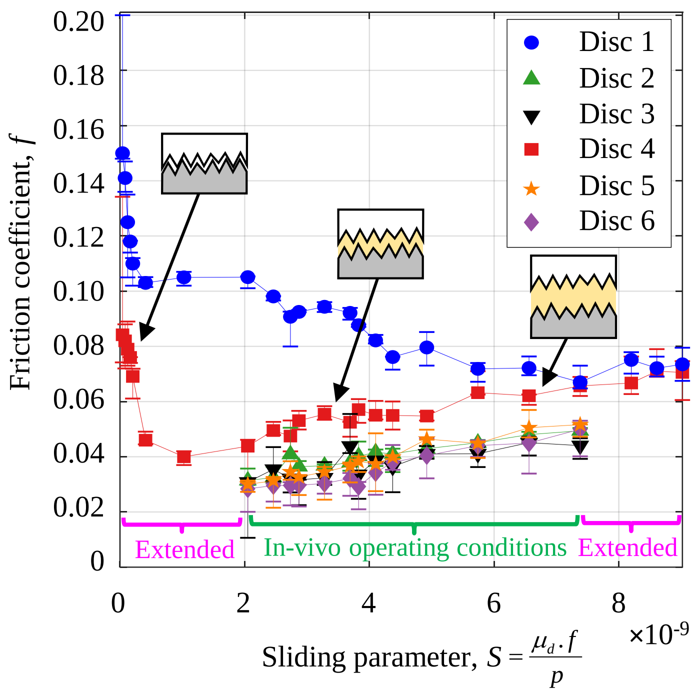
– Sliding parameter *S*, is defined as:

$$S = \frac{\mu_d . \omega}{p}.$$

  - μ_d : dynamic viscosity of the lubricant.
  - ω : cycle frequency.
  - p : contact pressure.

Short-duration friction coefficient experiments

- Polyethylene pin articulating with Disc 1 results in the highest friction coefficient, independent of the operating conditions.

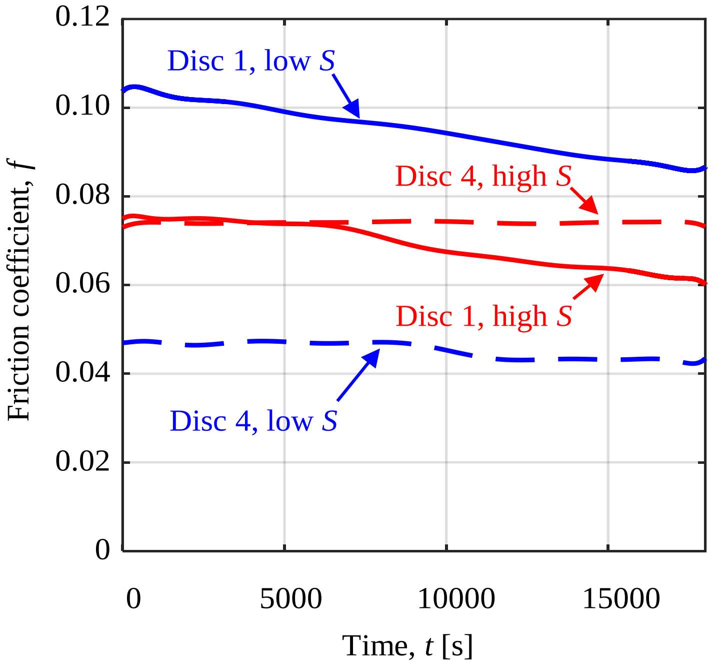


  - Friction coefficient:
    - Under in-vivo operating conditions:
      - **Disc 1:** decreases with increasing *S*.
      - **Disc 2-6:** increases with increasing *S*.
    - Under extended operating conditions:
      - **Disc 1:** decreases with increasing *S*.
      - **Disc 4:** first decreases with increasing *S*, and then increases.
  - The microtexture creates microhydrodynamic bearings, which increases the lubricant film thickness under constant operating conditions and accelerates the transition from **boundary/mixed** to **elastohydrodynamic lubrication.**
  - Disc 1 remains in the boundary lubrication regime throughout experiment.

Long-duration friction coefficient measurements (1)

- Five-hour PoD friction coefficient measurements to correlate friction coefficient with polyethylene wear.

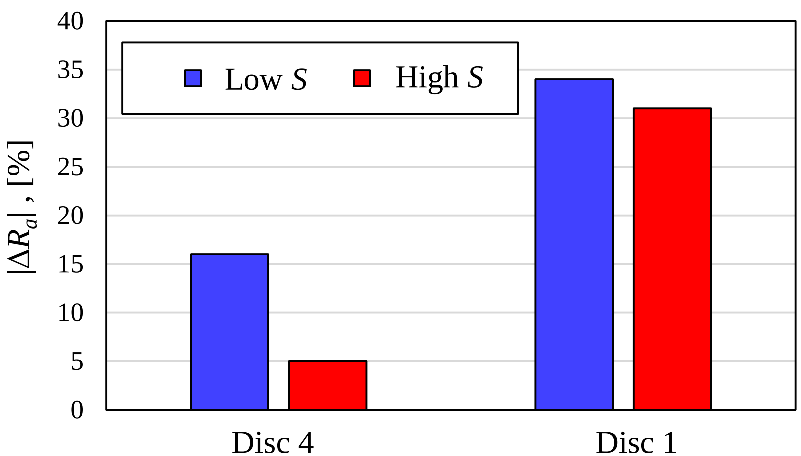
  - Friction coefficient:
    - **Disc 1:** higher friction coefficient under low *S* than high *S*, decreasing as a function of time.
    - **Disc 4:** higher friction coefficient under high *S* than low *S*, almost constant as a function of time.

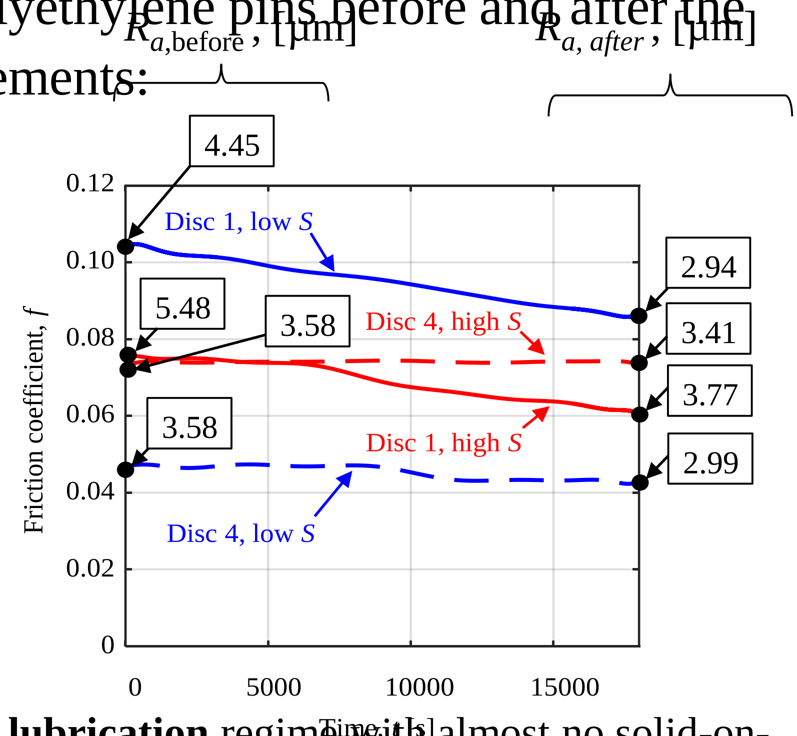


  - **Boundary/mixed lubrication regime**: the polyethylene surface undergoes polishing because the asperities wear, reducing the friction coefficient (**Disc 1**).
  - **Elastohydrodynamic lubrication regime**: the bearing surfaces are separated by a lubricant film, and the friction coefficient is only dependent on the shear stress in the lubricant (**Disc 4**). Minimal wear occurs.

Long-duration friction coefficient measurements (2)

- Average surface roughness (R_a) of the polyethylene pins before and after the long-duration friction coefficient measurements:
  - $\Delta R_a = (R_{a,\ after} - R_{a,\ before})/R_{a,before}$

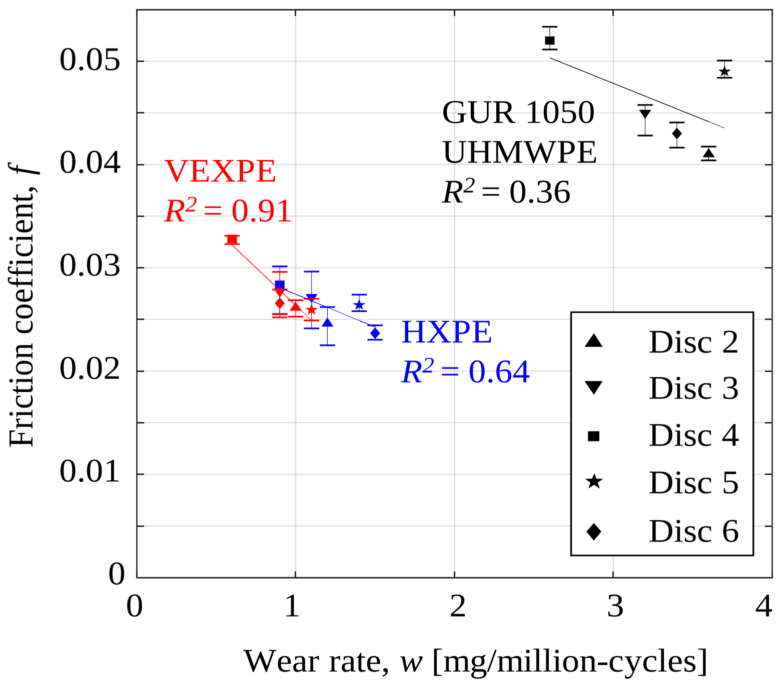




  - **Disc 4** operates in the **elastohydrodynamic lubrication** regime with almost no solid-on-solid contact between the pin and disc, demonstrated by a smaller ΔRa compared to Disc 1 (independent of *S*) .
  - **Disc 1** operates in the **boundary/mixed lubrication** regime, subject to wear and polishing, demonstrated by a larger ΔRa compared to Disc 4 (independent of *S*).
  - ΔRa decreases with increases *S* because the lubricant film thickness increases, reducing

Friction coefficient and wear rate correlation

- Quantifying the correlation between polyethylene wear rate and friction coefficient between polyethylene and CoCrMo.
  - Measure the friction coefficient of retrieved polyethylene pins from our previous wear experiments.
  - Same operating conditions as the wear experiments.
    - Polyethylene wear rate is inversely correlated to the friction coefficient.
    - R^2 decreases with increasing wear rate.



  - Under **elastohydrodynamic lubrication**, a higher friction coefficient between the pin and disc indicates a thicker lubricant film, which in turn reduces contact and polyethylene wear.
  - The instantaneous friction coefficient does not correlate well with cumulative wear, because it is primarily driven by surface conditions

Conclusions of friction coefficient measurements

- The lubrication regime between a polyethylene pin and a CoCrMo disc, under operating conditions relevant to in-vivo prosthetic hip implants, changes from boundary/mixed lubrication to elastohydrodynamic lubrication by manufacturing a microtexture of shallow concave "dimples" on the surface of the CoCrMo disc.

- Microtexture can primarily benefit the longevity of hip implants for high-activity patients with low body mass (high *S*), as opposed to high body mass, low-activity patients.

- Instantaneous friction coefficient measurements do not accurately represent the cumulative polyethylene wear rate in PoD wear experiments.

Overview

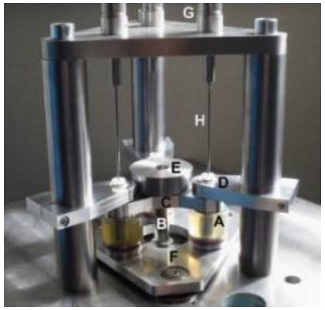
- Background review
- Simulation of microtextured surface lubrication
- Instrumentation and materials
  - Design and implementation of pin-on-disc testers
  - Manufacturing CoCrMo discs and polyethylene pins
- Results
  - Wear experiments of polyethylene pins against CoCrMo discs
  - Friction experiments of polyethylene pins against CoCrMo discs
  - A data-driven model of polyethylene wear
- Summary of achievements

A data-driven model of polyethylene wear (1)

- Polyethylene wear experiments are time consuming:
  - Polyethylene displays very low wear under in-vivo hip operating conditions.
  - Polyethylene is a viscoelastic material, which requires performing experiments at the in-vivo strain rate.

- Different wear experiments are difficult to compare:
  - Different research groups.
  - Different operating conditions.
  - Different devices.
    - Examples of three different devices to measure polyethylene wear:

http://www.orthoinno.com/

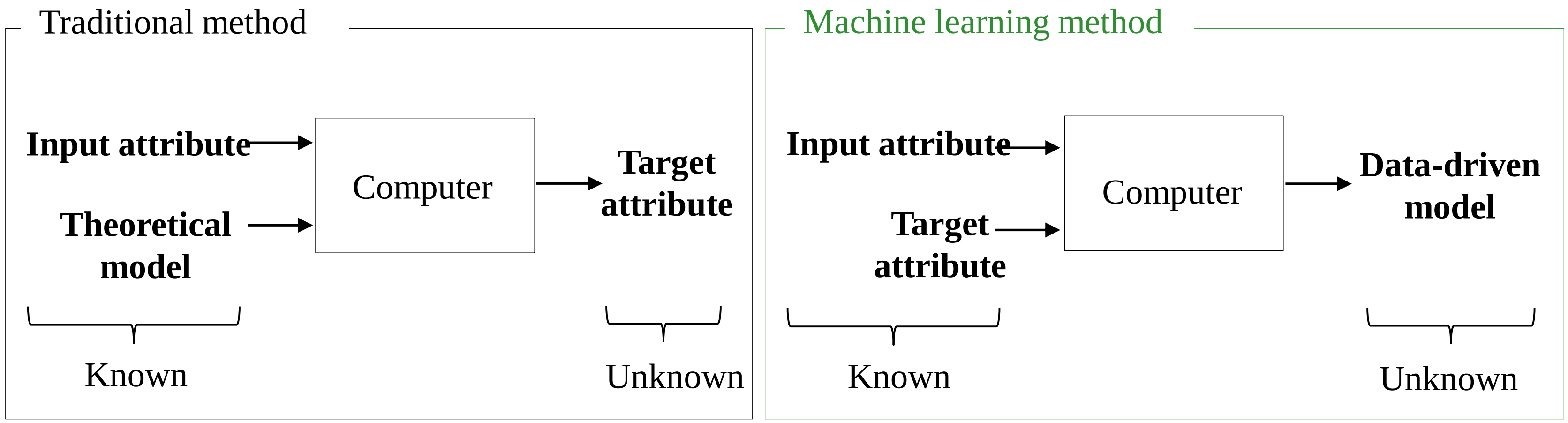


V. Saikko, J. Biomech. 48 (2015) 401–404

https://www.aalto.fi/department-of-mechanical-engineering

A data-driven model of polyethylene wear (2)

- Machine learning methods applied to existing datasets facilitate modeling complex relationships between material constituents, structure, and the corresponding mechanical properties.
- A data-driven model enables comparing existing datasets and predicting new results based on the existing knowledge, which are otherwise difficult or time-consuming to obtain using traditional experimental methods.



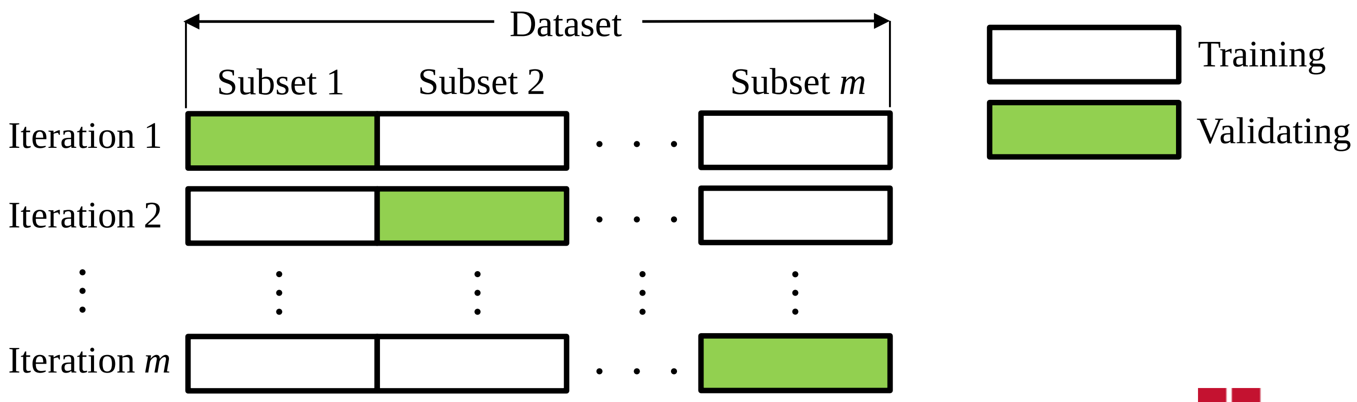
Published literature of PoD polyethylene wear

- Aggregate published polyethylene wear data from PoD experiments documented in the literature, conducted by others in the context of prosthetic hip implants (129 data points).

	Minimum	Maximum	Average	Standard deviation	Missing values	Stability [%]
Publication year	2001	2018	2008	6	0	20.16
Normal load [N]	7	777.55	166.26	129.38	0	28.68
Contact area [mm^2]	7.07	706.86	67.15	67.11	0	35.66
Frequency [Hz]	0.2	2	1.25	0.43	0	44.19
Sliding distance [mm]	17.76	94.25	30.47	10.08	0	30.23
Wear path shape	Rectangle 10 × 20 mm (used in 1 experiment)	Circle *d* =10 mm (used in 39 experiments)	-	-	0	30.23
Wear path aspect ratio	1	10.98	1.79	1.58	0	49.61
Lubricant temp. [°C]	20	37	29.23	7.50	63	46.97
Lubricant protein concentration [mg/ml]	0.69	64.8	22.28	6.35	33	36.46
Average disc surface roughness R_a [μm]	0.001	0.50	0.05	0.10	1	19.38
Polyethylene radiation dose [kGy]	0	150	36.31	40.77	0	40.31
Test duration [MC]	0.1	3.2	2.02	0.93	0	28.68
Polyethylene wear rate [mg/MC]	0.00	34.62	5.73	6.36	0	1.55

Machine learning methods (1)

- Three types of machine learning methods:
  - Interpretable model-based (e.g. CART decision tree).
  - Non-interpretable model-based (e.g. ANN).
  - Instance based (e.g. KNN).
- Tenfold cross-validation:
  - Randomly divides the dataset into m = 10 equal subsets.
  - m-1 subsets to train the data-driven model.
  - One remaining subset (not used for training) to validate the model.
  - Repeat this process m times such that the model is validated on the entire dataset.



Machine learning methods (2)

- Three commonly used metrics to evaluate the prediction error of a data-driven model.

Mean absolute error (*MAE*):

$$MAE = \frac{\sum_{i=1}^{n} |a_i - p_i|}{n},$$

Root mean square error (*RMSE*):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (a_i - p_i)^2}{n}},$$

Square of the correlation coefficient (R^2):

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (a_i - p_i)^2}{\sum_{i=1}^{n} (a_i - \bar{a})^2}.$$

  – a_i: the actual value of the i^{th} data point.
  – p_i: the predicted value of the i^{th} data point.
  – n: the total number of data points in the dataset.

Machine learning methods results

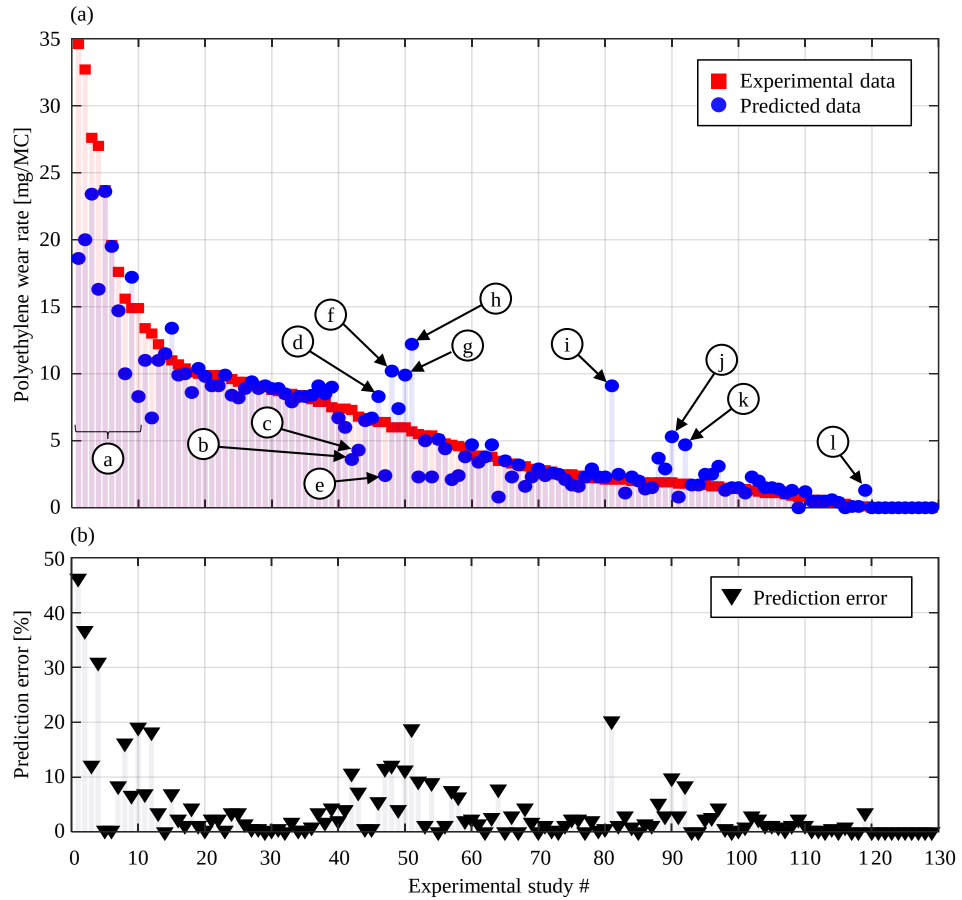
- Use each machine learning method to establish a data-driven model.
- Compute the three error metrics for each data-driven model.
- The KNN method results in the best lowest prediction error, determing the polyethylene wear rate within 1.38 mg/MC for any new PoD experiment.

Method	***MAE***	***RMSE***	***R^2***
Model-based (interpretable)			
Linear Regression	3.44	4.72	0.71
CART	1.95	3.35	0.83
M5	3.13	4.82	0.78
Random Forest	2.87	4.04	0.75
Gradient boosting	2.69	4.03	0.72
Model-based (non-interpretable)			
ANN	3.33	4.86	0.73
SVM	3.20	4.45	0.69
Instance-based			
KNN	1.38	2.37	0.91

- The relationship between the operating parameters and the polyethylene wear rate is not easily captured by one single model.

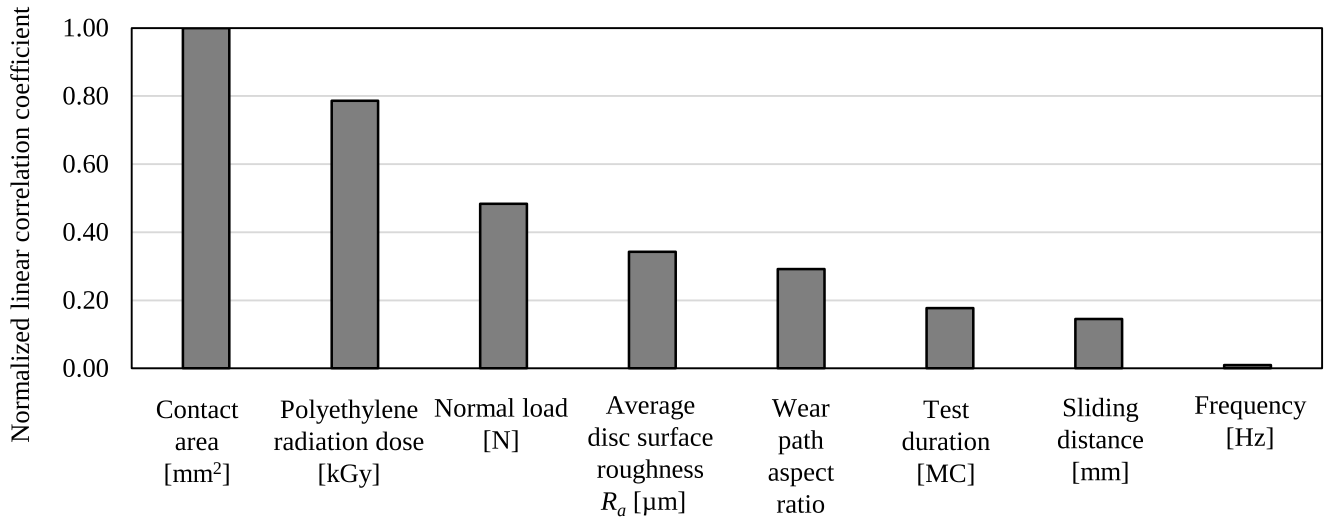
Outlier detection and new result validation

- A data-driven model based on the published literature facilitates validating new experiments and detecting outlier results, by comparing them to results in the literature.
  - **(a) not enough data.**
  - **(b)** and **(d)** lubricant was changed mid experiment.
  - **(c) used lubricant with the highest protein concentration.**
  - **(g)** used lubricant with the lowest protein concentration.
  - **(k)** and **(e)** used vitamin-E infused polyethylene.
  - **(f)** is the only study with 0.2 frequency.
  - **(h)** performed heat treatment.
  - **(i) and (j) used highest aspect ratio that is almost linear.**
  - **(l)** smallest force below recommended ASTM.



Relative contribution of all input attributes

- The data-driven model shows the relative contribution of all input attributes with respect to the resulting polyethylene wear rate.



- Assists researchers with the design of experiment by identifying and ranking the importance of operating parameters.
- Allows prioritizing the order in which to include operating parameters in future PoD wear experiments.

Conclusions of data-driven model of polyethylene wear

- A data-driven model allows predicting the polyethylene wear rate for new PoD experiments, within the operating envelope of the parameters used to train the model. This could potentially reduce the need for more experimental studies or shed light on experiment design.

- The KNN method results in the lowest prediction error, because the PoD polyethylene wear rate dataset cannot easily be captured by a single model.

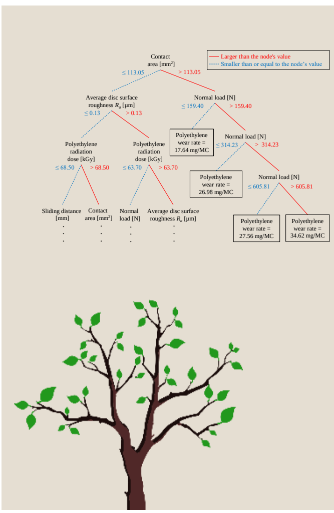
- This data-driven model facilitates validating new experimental results and detecting outliers, by comparing them to results in the literature, and also reveals the relative contribution of PoD wear experiment operating parameters to the polyethylene wear rate.

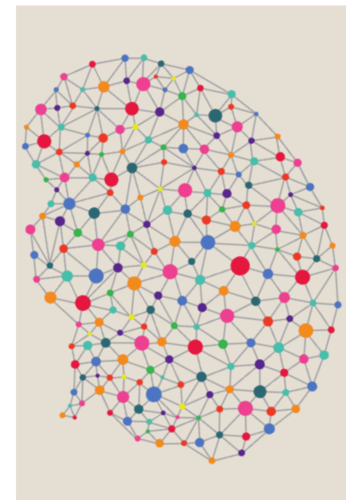
Achievements

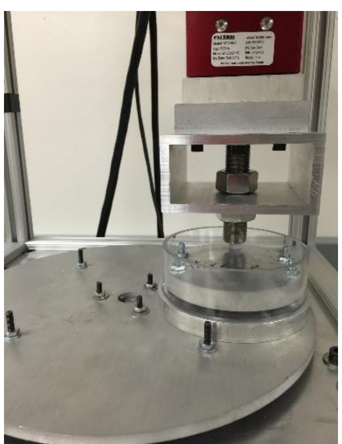
- **Journal publications:**
    1. **Borjali A**, Langhorn J, Monson K, and Raeymaekers B, “Using a patterned microtexture to reduce polyethylene wear in metal-on-polyethylene prosthetic bearing couples.” Wear, vol. 392, pp. 77–83, Dec. 2017
    2. Langhorn J, **Borjali A**, Hippensteel E, Nelson W, Raeymaekers B, “Microtextured CoCrMo alloy for use in metal-on-polyethylene prosthetic joint bearings: Multi-directional wear and corrosion measurements.” Tribology International, vol. 124, pp. 178-183, Aug. 2018
    3. **Borjali A**, Monson K, Raeymaekers B, “Friction between a polyethylene pin and a microtextured CoCrMo disc, and its correlation to polyethylene wear, as a function of sliding velocity and contact pressure, in the context of metal-on-polyethylene prosthetic hip implants.” Tribology International, vol. 127, pp. 568-574, Nov. 2018
    4. **Borjali A**, Monson K, Raeymaekers B, “Predicting the polyethylene wear rate in pin-on-disc experiments in the context of prosthetic hip implants: a data-driven model based on experimental data and machine learning methods” (submitted for publication, under review)

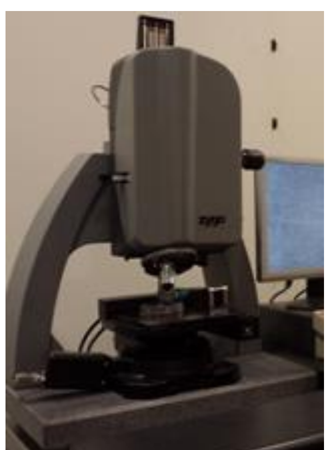
- **Conference publications:**
    1. Langhorn J, Hippensteel E, Schmidt D, **Borjali A**, Raeymaekers B, “Microtexturing to reduce wear in orthopaedic device bearing couples,” Proc. of Material Science and Technology Conference, Pittsburgh, PA (USA), 9-12 Oct. 2017
    2. **Borjali A**, Langhorn J, Monson K, and Raeymaekers B, “Using a patterned microtexture to reduce polyethylene wear in metal-on-polyethylene prosthetic bearing couples,” 2018 STLE Tribology Frontiers Conference, Chicago, IL (USA), 28-31 Oct. 2018 (accepted)

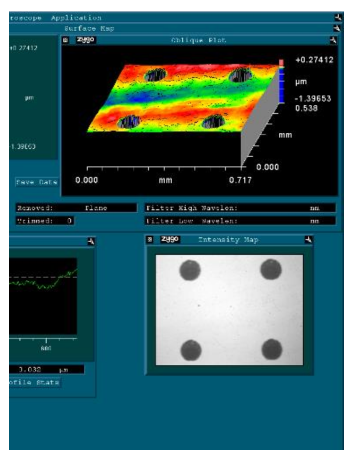
Questions?


Contact
area [mm^2]
Larger than the node's value
Smaller than or equal to the node's value
≤ 113.05
> 113.05
Average disc surface
roughness R_a [μm]
≤ 0.13
> 0.13
Normal load [N]
≤ 159.40
> 159.40
Polyethylene
radiation
dose [kGy]
≤ 68.50
> 68.50
Polyethylene
radiation
dose [kGy]
≤ 63.70
> 63.70
Polyethylene
wear rate =
17.64 mg/MC
Normal load [N]
≤ 314.23
> 314.23
Polyethylene
wear rate =
26.98 mg/MC
Normal load [N]
≤ 605.81
> 605.81
Sliding distance
[mm]
Contact
area [mm^2]
Normal
load [N]
Average disc surface
roughness R_a [μm]
Polyethylene
wear rate =
27.56 mg/MC
Polyethylene
wear rate =
34.62 mg/MC








Surface Map
Oblique Plot
+0.27412
µm
-1.39653
0.538
mm
0.000
0.000
mm
0.717
Removed: Plane
Trimmed: 0
Intensity Map