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Enhancing Cross-Linked UHMWPE Knee Prosthesis Design: A Comprehensive Approach to Assessment and Optimization

Farah Hamandi[1], Evan Helton[1], Mikayla Padgitt[1], Tarun Goswami[1,2]

1, Department of Biomedical, Industrial, and Human Factors Engineering, Wright State University, Dayton, OH 45435, USA

2, Department of Orthopedic Surgery, Sports Medicine and Rehabilitation, Wright State University, Dayton, OH 45435, USA

INTRODUCTION

Osteoarthritis (OA) stands as the predominant form of arthritis, holding the position of the most prevalent cause of disability among adults in the United States [1]. Globally, prevalent cases of OA increased by 113.25%, from 247.51 million in 1990 to 527.81 million in 2019 [1]. With more than half of individuals experiencing symptomatic OA necessitating knee replacement [2], the demand for knee implants that are both durable and comfortable has reached unprecedented levels. The primary factor contributing to joint replacement failure is loosening, a condition induced by osteolysis. Osteolysis, in turn, results from the presence of wear debris generated from the polyethylene articulating surfaces of the implant. These articulating surfaces are susceptible to oxidation, rendering them more brittle and prone to wear over time.

RESEARCH GOAL

This research integrates multiple facets to enhance the durability and performance of knee liners. The study assesses the durability of twelve retrieved knee liners made of cross-linked, ultra-high molecular weight polyethylene. The study links damage patterns with stress development and introduces an upscaled knee liner design.

METHOD

Twelve knee liners, crafted from cross-linked ultra-high molecular weight polyethylene (UHMWPE), underwent rigorous assessment to enhance their durability and performance. The in-depth investigation encompassed four distinct *in vivo* damage assessment methods, namely Wasielewski, Brandt, Lombardi, and Hood. The damage modes were meticulously quantified through optical and confocal microscopy techniques, providing a detailed understanding of wear characteristics (1).

$$\text{Damage Score} = \text{Severity Score} \times \text{Area Score} \qquad (1)$$

Precise computer-aided drawings (CAD) were generated to facilitate finite element analysis (FEA) of each knee liner, the tibial, and femoral components. The FEA outcomes were correlated with surface evaluations, establishing a quantitative link between structural integrity and in vivo damage (2).

$$\text{Correlation} = \text{Surface\_Evaluations} / \sum \text{FEA\_Outcomes} \qquad (2)$$

Building on this foundation, Optical and confocal microscopy techniques were employed to quantify wear characteristics. Computer-aided drawings (CAD) facilitated finite element analysis (FEA), correlating FEA outcomes with surface evaluations. An upscaled knee liner design was introduced and evaluated using ANSYS and fatigue life prediction models, optimizing design parameters in SolidWorks.

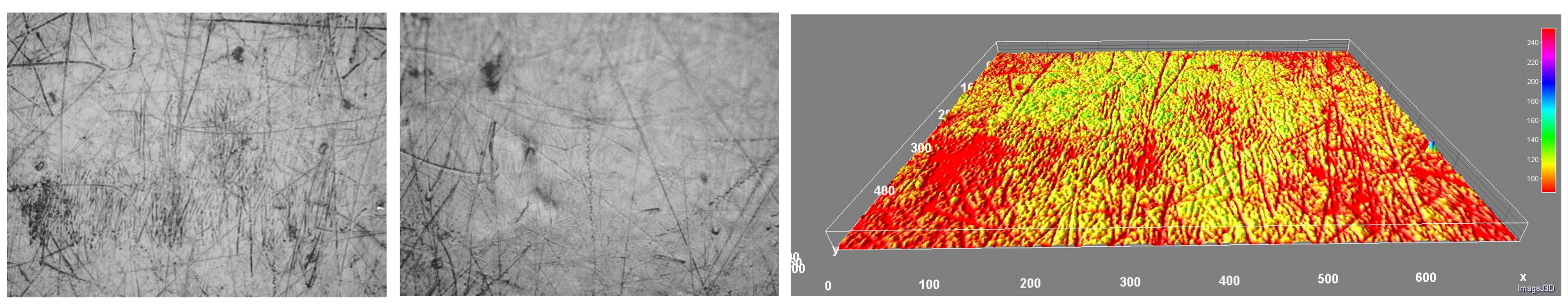

Figure 1. Microscopic Surface Images showing scratches

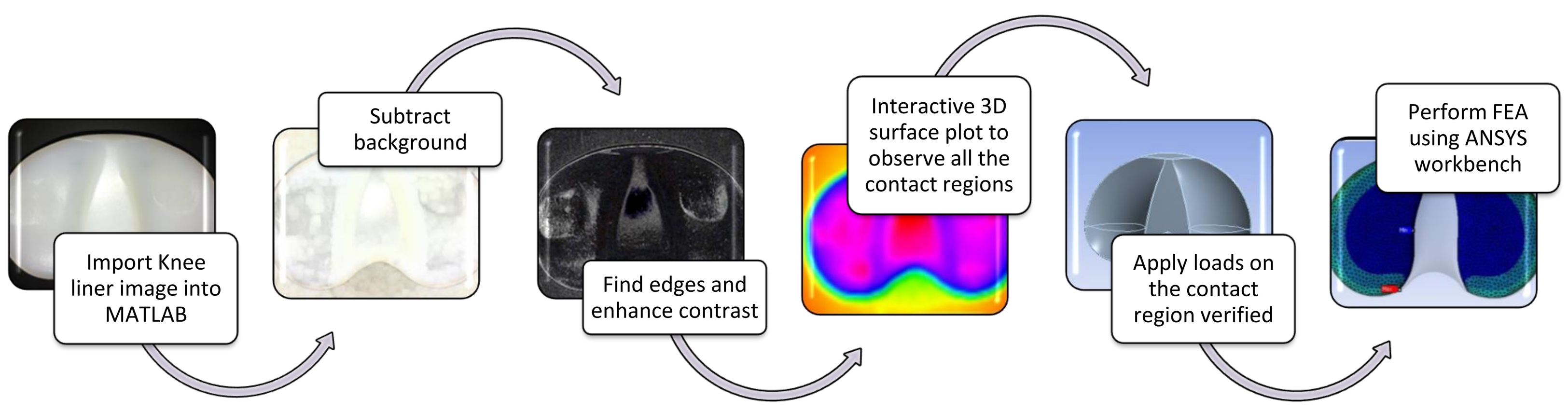

Figure 2. The process of observing the contact regions by using MATLAB then applying gait cycle loads on the verified contact areas and performing FEA

RESULTS

The integrated approach demonstrates promising advancements in structural integrity, performance, and optimization of knee liners. Correlations between FEA outcomes, surface evaluations, and gait analysis provide comprehensive insights. The combination of Ansys and SolidWorks functionalities proves effective in advancing knee prosthesis design, with implications for future material advancements and improved durability and performance. The overall stress improvements range from 11.48% to 16.75% depending on the activity and gender. The anterior-posterior (A-P) stress shows an improvement range of 11.69% to 20.82%. The medial-lateral (M-L) stress improvements are generally more significant, with increases ranging from 12.00% to 23.54%.

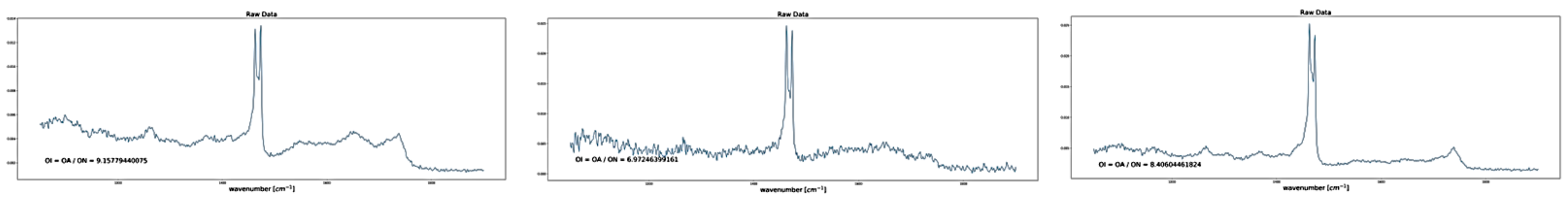

Figure 3. The absorption spectrum produced through oxidation testing

Table I. The oxidation values for the investigated liners and predicted tensile strength values

Liner #	Oxidation Index	Predicted Ultimate Tensile Strength (MPa) values at different crosslinking doses		
		50 kGy	75 kGy	100 kGy
1	0.716	29.5	30.2	34
2	1.164	25.2	25.6	26.8
3	0.997	25.5	26	28.4
4	0.707	29.7	30.4	34.3
5	0.757	28.6	29.2	33
6	0.923	26.3	26.9	30
7	0.841	27.1	27.6	31.2
8	1.045	24.9	25.3	27.1
9	0.685	30	30.6	34.7
10	0.772	28.4	29	32.8
11	0.915	26.5	27.1	30.2
12	0.805	27.6	28.1	32
Average	0.858	27.64	28.22	31.33

Table II. The crystallinity percentage and hardness values for the investigated liners

Liner #	% Crystallinity	Hardness (Shore D)		
		Top (articulation)	Bottom (fixed)	Average
1	50.96	31.4	56.5	43.9
2	24.05	40	68	54
3	47.79	40.3	72.2	56.3
4	58.09	32	68.6	50.3
5	48.64	46.6	68.1	57.4
6	49.75	34.8	65	49.9
7	46.23	36.5	66.3	51.4
8	52.19	33	64.7	48.9
9	50.15	31.8	67.1	49.4
10	45.88	38.6	70.2	54.4
11	53.02	37.5	69	53.3
12	47.35	42	71.3	56.7
Average	48.04	37.57	67.06	52.32

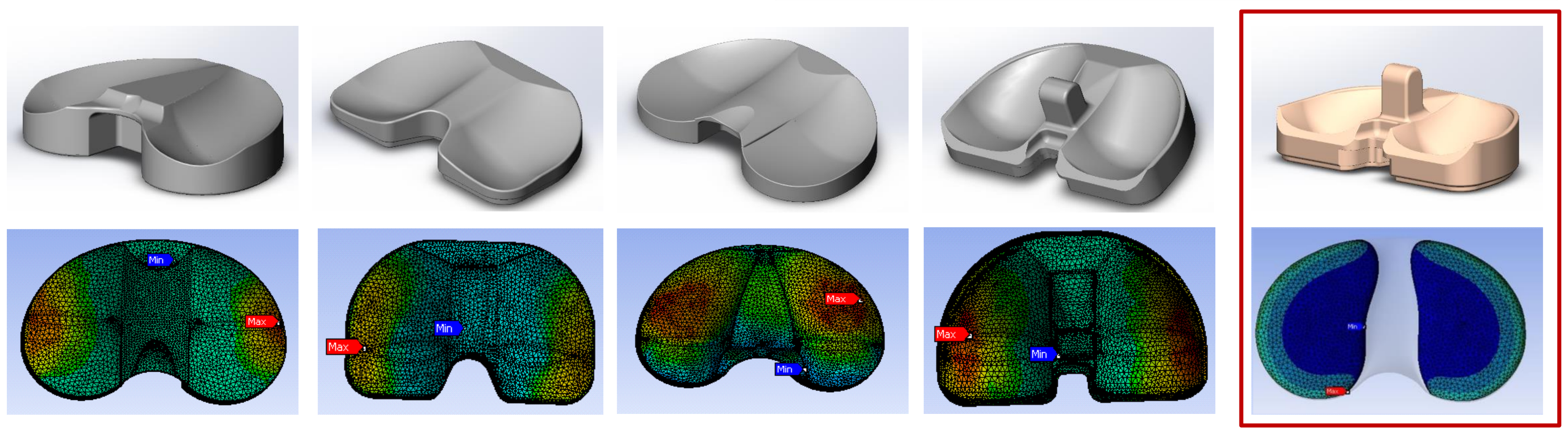

Figure 4. Knee liners 3D models (Top) maximum stress patterns (Bottom) comparing previous designs (left) to the proposed upscaled knee liner design (right).

Table III. Maximum von Mises stresses and fatigue life predictions

Activity	Gender	Twelve UHMWPE knee liners				Modified Liner			
		Max Stress Overall (MPa) (Mean ± STD)	Max Stress A-P (MPa) (Mean ± STD)	Max Stress M-L (MPa) (Mean ± STD)	Fatigue Life Prediction (Cycles)	Max Stress Overall (MPa)	Max Stress A-P (MPa)	Max Stress M-L (MPa)	Fatigue Life Prediction (Cycles)
Level Walking	Male	7.46 ± 1.31	6.29 ± 1.18	5.27 ± 1.01	2.1×10^{10}	8.71	7.6	6.12	5.8×10^{10}
Stairs Up		8.18 ± 1.08	7.31 ± 1.07	6.35 ± 0.91		9.12	8.23	7.14	
Stairs Down		7.94 ± 1.07	6.93 ± 1.09	5.88 ± 0.84		8.95	8	6.87	
Level Walking	Female	7.08 ± 1.13	6.10 ± 1.04	4.67 ± 1.03		8.05	6.96	5.23	
Stairs Up		6.74 ± 1.11	5.90 ± 1.01	4.80 ± 1.10		7.84	6.59	5.93	
Stairs Down		7.36 ± 1.08	6.39 ± 1.05	5.04 ± 1.01		8.47	7.21	6.02	

CONCLUSION

Linking damage patterns with stress development is crucial, with computational simulations playing a key role in validating techniques. The upscaled knee liner design and advanced fatigue life prediction models demonstrate potential for enhancing knee prosthesis durability and performance, ultimately benefiting patients undergoing knee replacement surgeries.

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