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Investigating Effects of Testing Parameters on Frictional Heating of UHMWPE by Taguchi Method

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Frictional heating makes detrimental effects on surrounding tissue and lubricant around the artificial hip joint. For reduction of this thermal damage, testing parameters and their effects were investigated by using the Taguchi method and analysis of variance. Ultra high molecular weight polyethylene (UHMWPE) acetabular liners and CoCrMo femoral head artificial hip joint components were used as samples. Frictional heating measurements of the joints were carried out on a custom made hip joint friction experimental setup. Surface dimples in different sizes were machined on the inner surface of acetabular insert samples. The tests were conducted under different loading conditions with different testing time. Bovine calf serum was used as lubricant with different amount of third body wear particles in it. Temperature rise in acetabular and femoral component was recorded with embedded thermocouples. The experimental results demonstrated that the surface dimples were the major parameter on frictional heating, followed by applied load, amount of third body particles and time. The optimal combination of the testing parameters was predicted and validated by doing experiments.

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1. Introduction

Frictional heating makes detrimental effects on surrounding tissue and lubricant around the artificial hip joint. In previous studies both *in vivo* and *in vitro*, it was reported that the frictional temperature rise may reach 6–7 °C [1–3]. This heating could cause protein precipitation from the synovial fluid around the hip joint. Also this heating may damage the surrounding tissue and bone cells. So it decreases the service life of the artificial hip joint. For reducing the frictional heating and obtain better lubrication condition, the inner surface of the UHMWPE acetabular insert was patterned with 0.5 mm and 0.3 mm in diameter dimples. Actually, to reduce the friction coefficient of the sliding materials, surface patterning has been one of the popular method for frictional surfaces [4, 5]. In some previous study surface patterning was tried on UHMWPE disc surface for determining the wear behavior of the material [6, 7]. But there are very few studies on applying surface patterning to the inner surface of UHMWPE acetabular component. There is no enough study about effect of surface dimples on frictional heating of UHMWPE [8]. Also there is no consensus about dimensions of dimples. For conserving the efficiency of dimples under high contact pressure, it is important to define optimum dimple dimensions under different testing conditions. In previous studies surface patterning was generally applied on disc samples surfaces. But for obtaining more reliable results it is important to use samples in real geometry.

The objective of this study is to determine the effect of surface dimples and their dimensions on frictional heating of artificial joint materials. Besides this it is aimed to define the influence of the applied load, third body particles amount, and walking time on frictional heating of UHMWPE acetabular insert.

2. Materials and methods

UHMWPE acetabular liner samples were machined from Chirulen 1020 rods (MediTECH Medical Polymers, Vreden, Germany) in accordance with ISO 7206-2:2011 and ISO 21535 [9, 10]. The acetabular liner samples were paired with commercially available CoCrMo femoral heads. The prostheses were in 28 mm diameter. Surface roughness of the samples has been measured by Taylor Hobson Form Talysurf Intra. Surface roughness of UHMWPE was 0.670 μm and of CoCrMo 0.02 μm. These values are suitable for the reference of ISO 7206-2:2011 [9]. Three groups of acetabular liners were manufactured. First group was unpatterned one. On second and third group liners' surfaces, 0.3 mm and 0.5 mm in diameter surface dimples were machined by five axis computer numerical control milling machine. CAD/CAM model of the patterned liners can be seen in Fig. 1a.

Frictional measurements of the joints were carried out on a custom made hip joint friction simulator. The details of the simulator were given in our previous studies [11–14]. The experimental setup can be seen in Fig. 1b.

A standard Taguchi experimental plan with notation L9(3^4) was chosen. The experimental results were transformed into signal-to-noise (S/N) ratio as a quality characteristic to measure the deviation from desired values. In the analysis of S/N ratio there are three types of quality characteristic such as the-lower-the-better, the-higher-the-better and the-nominal-the-better [15]. In

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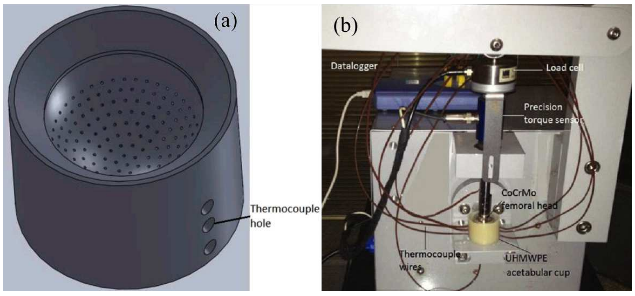

Fig. 1. (a) 3D CAD model of the acetabular insert with surface dimples and thermocouple holes, (b) experimental setup.

present study the-lower-the-better quality characteristic was chosen due to investigating the frictional heating of artificial joint materials. Besides this, to define which test parameters were statistically significant on frictional temperature rise, analysis of variance was performed. So it could be possible to predict the optimal combination of the testing parameters for a 95% confidence level with S/N ratio and ANOVA analyses. Lastly, for verifying the optimal testing parameters, confirmation tests were conducted. Control factors and their levels can be seen in Table I.

TABLE I

Control factors and their levels.

Level	Factors			
	Surface	Load [N]	PMMA [mg]	Time [h]
1	unpatterned	750	0	1
2	0.3 mm patterned	1000	25	2
3	0.5 mm patterned	1500	50	3
factor code	*A*	*B*	*C*	*D*

For representing 75, 100, and 150 kg body weights 750, 1000, and 1500 N static loads were applied. In flexion--extension plane, a simple harmonic oscillatory motion between $\pm 24°$ is applied to the acetabular component. The period of motion was 1 Hz and the tests were run up to 1, 2 and 3 h for simulating different walking durations. 5 ml, 25% bovine calf (Sigma-Aldrich) serum was used as lubricant. To avoid bacterial contamination 0.3% sodium azide and 5 mM EDTA was added to the lubricant. For determining third body abrasive effect on frictional heating of UHMWPE acetabular component, 25 mg and 50 mg polymethyl methacrylate (PMMA) bone cement was added to the sliding surfaces of the joint.

3. Results and discussion

Frictional temperature rises were recorded during different walking times. The tests were repeated at least three times for each experiment condition. Temperature values were collected per cycle that means each second. The data logger program gives the temperature values with two digits after the decimal point and we did not round them up or down, just used the values as recorded. The experimental layout and average temperature rise results with S/N ratios were presented in Table II.

TABLE II

Experimental layout and results with calculated S/N ratios.

Exp. no.	Factor codes and levels				Average frictional temperature rise [°C]	S/N
	A	*B*	*C*	*D*		
1	0	750	0	1	8.07	−18.1379
2	0	1000	25	2	10.75	−20.6284
3	0	1500	50	3	14.92	−23.4755
4	0.3	750	25	3	6.34	−16.0527
5	0.3	1000	50	1	6.22	−15.8864
6	0.3	1500	0	2	6.86	−16.7230
7	0.5	750	50	2	8.29	−18.3679
8	0.5	1000	0	3	8.56	−18.6536
9	0.5	1500	25	1	10.51	−20.4357

The graphical representation of the average temperature rises can be seen in Fig. 2. It is clear from the results that surface patterning significantly reduced the temperature rise of the UHMWPE. The minimum temperature rises were recorded for 0.3 mm in diameter patterned samples. For unpatterned acetabular liner samples the temperature values were the highest. The surface dimples acted as reservoir for lubricant and they provided better lubrication. So friction coefficient and frictional temperature rise were decreased. Also, frictional temperature rises were increased by increasing applied static load, amount of PMMA and walking time. PMMA particles caused third body abrasive wear and scratch the surface of the both acetabular insert and femoral head. So the friction coefficient and frictional heating increased.

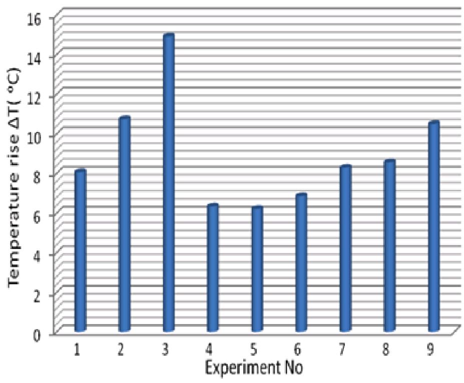

Fig. 2. Temperature rise for each experiment.

From main effects plot for S/N ratios in Fig. 3, it can be concluded that the optimal process parameters for minimum temperature rise as A2B1C1D1. While the surface is patterned with 0.3 mm diameter dimples, the load is 750 N, PMMA amount is 0 mg and the walking time

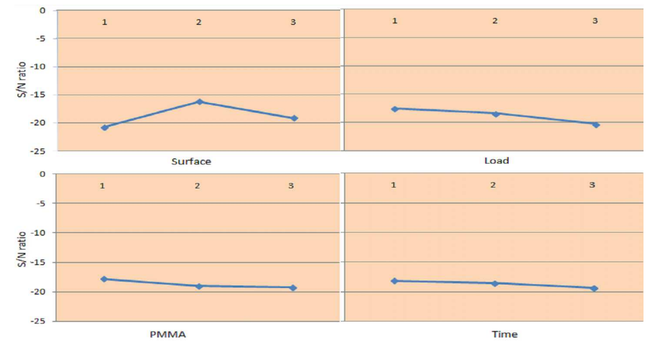

Fig. 3. Main effects plot for S/N ratios.

is 1 h. The confirmation tests were conducted by using these parameters. The average temperature rise value was measured as 4.21 °C. The predicted temperature rise value by Taguchi model was 3.3 °C. Both these values were lower than the values in experimental design. So it can be said that the A2B1C1D1 are the optimal process parameters. For defining if the parameters were statistically significant the analysis of variance was performed. The F values for design parameters were calculated by using sum of squares of the factors. F value for factor A was 3469.88, for B was 1655.79, for factor C was 629.21 and for D was 463.40. For 95% confidence level, the degree of freedom for factors was 2 and for error was 18. So the F value read from the table was: F_{table} 0.05 (2, 18) = 3.55. Calculated F values for all factors were bigger than F_{table}. So it means that the design parameter showed a significant effect on the frictional heating of UHMWPE acetabular insert.

In our previous study [13] we investigated the effect of 0.5 mm diameter surface dimples on frictional heating. In this study we compared the different surface dimple dimensions and testing conditions effects on frictional heating of conventional UHMWPE. For determining optimal surface characteristics and material combinations, our experiments are going on with different surface textures and material pairs.

4. Conclusion

The effects of the textured surfaces may decrease friction and wear between two sliding surfaces. The surface dimples acted as reservoir for lubricant and provided better lubrication. So friction coefficient and frictional temperature rise was decreased. Also, frictional temperature rises were increased by increasing applied static load, amount of PMMA and walking time. PMMA particles caused third body abrasive wear and scratch the surface of the both acetabular insert and femoral head. So the friction coefficient and frictional heating increased. The Taguchi experimental design and analysis of variance results showed that surface patterning, loading, amount of PMMA and test duration parameters have significant effect on the frictional heating of UHMWPE acetabular insert.

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