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5 Numerical analysis of cartilage surfaces for Osteoarthritis  
6 diagnosis using field and feature parameters  
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16 **Abstract**  
17

18 Osteoarthritis (OA) is one of the most common degenerative wear diseases of knee joints worldwide. Within knee  
19 joint articular cartilage (AC), collagen structure losing integrity is a major symptom of OA. Based on the  
20 development of laser scanning confocal microscopy (LSCM), AC images containing three-dimensional (3D)  
21 surface texture information could be obtained for quantitative analysis using numerical parameters. Numerical  
22 analysis results could be applied for OA diagnosis and progression assessment. Unique to existing numerical  
23 analysis techniques, two surface texture parameter sets named field and feature parameters have been used to  
24 study wear features in this study. Field parameters are statistically applied to consecutive surface of each scale-  
25 limited surface portion while feature parameters are statistically used for a sub-set of pre-defined topographic  
26 features. In this study, the feature parameters are for the first time innovatively used for numerical analysis of  
27 wear testing AC samples. This project has also selected critical parameters from the field and feature parameter  
28 sets to study the correlation between the AC surface changes and OA development. The results presented in the  
29 paper have demonstrated that the selected field parameters describe the wear features of the surfaces for the study  
30 of OA progression and the selected feature parameters characterise surface features and their relationship for the  
31 study of the functional performance of the surfaces. By utilizing the proposed analysis approach, it is possible to  
32 enhance the current numerical analysis techniques for both OA status monitoring and problem diagnosis.  
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34 *Keywords:* Field and feature parameters; Articular cartilage; Surface texture; Numerical analysis; Osteoarthritis  
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## 1 *1. Introduction*

2  
3 Osteoarthritis (OA) is a worldwide articular cartilage (AC) progressive wear disease which  
4 affects majority of people under certain age group [1]. OA disease is also one of the top ranked  
5 disabling diseases and the treatment cost plus work-related losses is over \$33 billion annually  
6 in United States [2]. AC surface fibrillation and collagen matrix losing integrity sometimes with  
7 bone exposure are major symptoms of OA disease [3, 4]. Based on the erosion of total AC loss,  
8 OA could be classified into three degrees from OA grade 1 to 3 which stands for the severity of  
9 different disease stages [5].

10  
11 AC is a connective tissue and bony component located on the end of a synovial joint such as a  
12 knee joint. It is composed of different layer structures which are superficial layer, intermediate  
13 collagen network and calcified subchondral bone from surface to bottom [6, 7]. Existing  
14 studies have revealed that the cartilage surface texture changes with OA progression [8-10],  
15 and therefore can be used to assess OA conditions.

16  
17 To study the cartilage surface texture change, laser scanning confocal microscope (LSCM)  
18 could be employed as a powerful tool for target topography assessment. Compared with  
19 traditional scanning electronic microscope, LSCM has significant advantages in terms of zero  
20 or very limited sample preparation requirements and its capability of acquiring three-  
21 dimensional information. Other than two-dimensional information from a lateral x-y  
22 dimensions planar AC surface, LSCM could gather serial optical sections through z-direction  
23 step in scanning from a controlled field depth [11-13]. Appropriate 3D images collected  
24 through LSCM could be numerically analysed with surface texture parameters to study the AC  
25 surface changes with OA progression.

26  
27 Field and feature parameters are two defined sets of surface texture parameters compiled by  
28 ISO/FDIS 25178-2 [14]. The field parameters apply statistics to the continuous point cloud of  
29 areal surface texture data, which inherits the majority of the conventional 3D surface texture  
30 parameters. The feature parameters apply statistics from a subset of pre-defined topographic  
31 features [15]. This characterisation method adopts feature characterisation techniques, and it

1 can prune out those instable features [16], and it is expected to be more stable than the  
2 conventional surface texture parameters.

3  
4 All of the existing approaches use statistical descriptions (i.e., the traditional shape and profile texture  
5 parameters) to monitor changes in the particle shape and surface texture to indicate changes in the wear  
6 conditions of the joint. The parameters cannot assess functional performance of the joint directly, and  
7 therefore cannot be used as a diagnostic tool to study the cause of wear problems [16]. Wear in joints  
8 depends not only on the surface morphology of the counter-part cartilages which can be characterised  
9 using the above areal (field) parameters in 3D, but is also determined by their contact areas. To date,  
10 researchers have difficulty in measuring or predicting the contact areas between two wear components.  
11 Feature parameters have been developed to “characterise the functional topographical features of  
12 surfaces by analyzing texture shape and direction, estimation of feature attributes and differentiation  
13 between connected and isolated features” [17]. This new concept has opened a door for the study of OA  
14 causes and functional performance of the cartilage. Unique to the existing research, this study  
15 investigates the newly developed functional parameters for OA assessment.

## 16 17 18 *2. Wear Testing and Image Acquisition*

19  
20 Sheep joints were wear tested using a wear simulator to obtain cartilage samples with the  
21 defined degrees of OA. Specimen pieces were collected from tibia end, then fixed and stained  
22 for LSCM imaging. Images containing 3D surface information were numerically analysed  
23 using field and feature parameters. Statistical and correlation analysis was performed to  
24 examine the new parameters’ function for OA studies and then select critical numerical  
25 parameters to monitor AC surface texture change under wear progression.

### 26 27 **2.1 Wear Test**

28  
29 Three 11 months merino sheep assumed being in health joint conditions was used in this study.  
30 All the sheep were anesthetized and painless killed under strict approval from Animal Ethics  
31 Committee, James Cook University (JCU), Australia. Total six joints gathered from hind legs  
32 were fixed on a wear simulator set up in the mechanical engineering laboratory at JCU. The  
33 wear tester [18] could simulate normal walking motion with the assistance of an airbag which

1 was attached to offer variable loading to the testing joints. One joint was chosen as control  
 2 joints and the other five were tested in different time spans to produce specimens with OA  
 3 grade 1 to 3. Testing conditions of the joints are shown in Table 1.

4  
 5 Table 1 Testing conditions and OA degrees of the six sheep knee joints.

Joint No.	Load (kg)	Testing Cycles	Degree of OA
Control	0	0	0
Joint 1	15	10,000	1
Joint 2	15	12,000	1,2
Joint 3	15	17,000	2
Joint 4	15	26,000	2,3
Joint 5	15	37,000	3

6  
 7 Once the tests were completed, the joint cavity was cut open and three cartilage pieces sized  
 8 approximately 8mm\*5mm\*3mm in length, width and thickness were collected from the tibia  
 9 end using a surgical kit. The collected AC samples were then immersed into 2% glutaraldehyde  
 10 and stored in 4°C fridge over 24 hours for fixations. The fixed cartilage pieces were then  
 11 stained in 0.03g/l Rhodamine B solution and delivered for image acquisition using the LSCM  
 12 located at Advanced Analytical Centre (AAC), JCU.

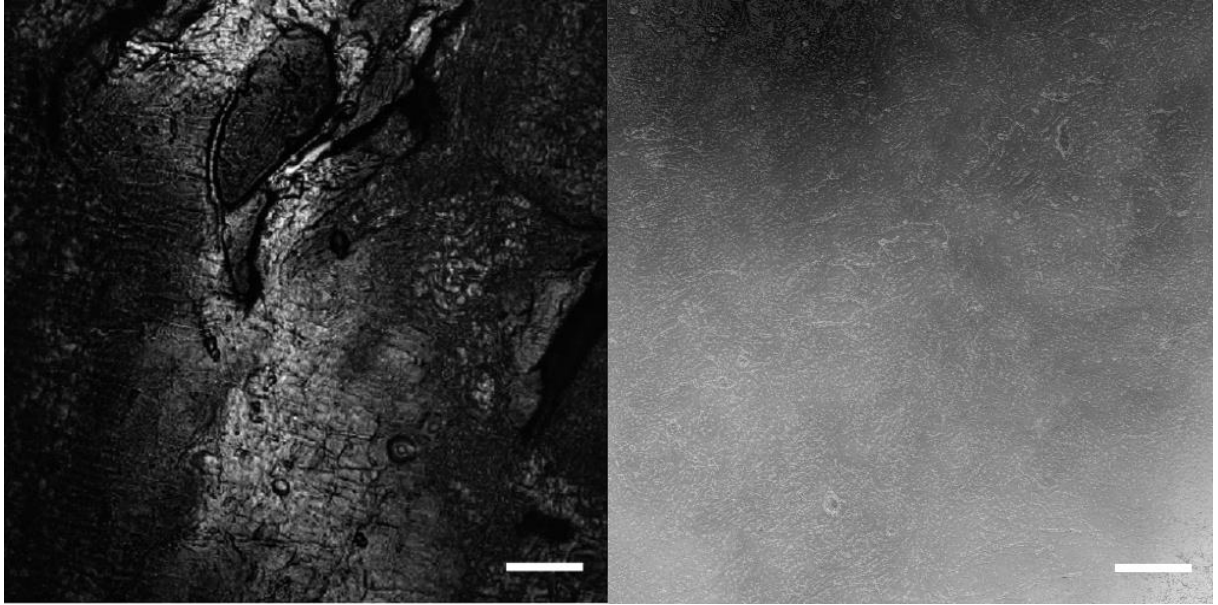
13  
 14 **2.2 Image Acquisition and Imaging Process**

15  
 16 Since Rhodamine B has an excitation/emission wavelength of 533nm/619nm [19], 514 nm  
 17 Argon ion laser of LSCM with an open emission filter of 530/60nm was therefore used for the  
 18 image scanning in the study. Three scanning points were selected from each surface of the  
 19 three AC samples. Therefore, eight to nine cartilage images were acquired from each joint of  
 20 the 5 tested joints, i.e., Joint 1 to 5. For the control joint, as the health joint surface has a very  
 21 homogeneous surface texture, only four cartilage surface images were collected.

22  
 23 Under LSCM 40x objective lens and 0.66mw to 0.88mw 514nm Argon laser, a 512\*512 pixels  
 24 images stack was gained with a 0.2 μm z-direction step size scanning. Then the images stacks

1 were processed using image processing codes developed in Matlab 6.5 package to generate a  
2 Height Encode Image (HEI) containing 3D surface information of the AC samples, followed  
3 by filtering and numerical analysis with field and feature parameters, which will be presented  
4 in the following separate section. An image of Joint 2 cartilage surface and a Joint 4 visually  
5 enhanced HEI image are in shown Figure 1.

6



7

8 Fig.1. (a) 40x Joint 2 cartilage surface image; (b) 40x Joint 4 visually enhanced HEI image; scale bar=50  $\mu\text{m}$ .

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### 3. Numerical Analysis and Results

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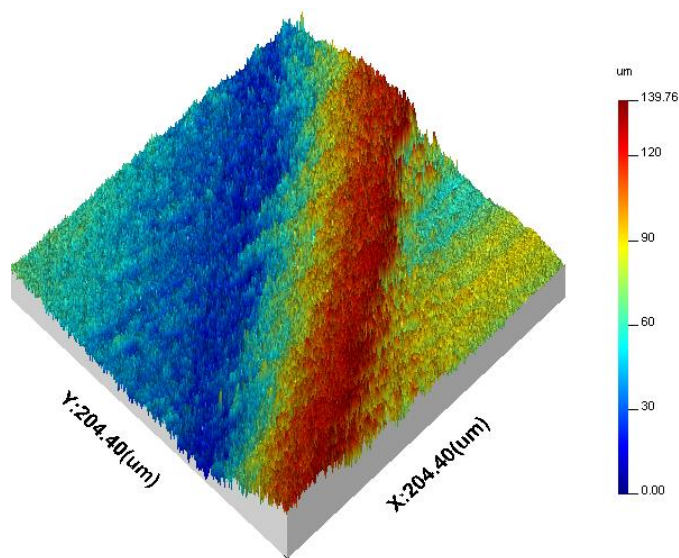
#### 3.1 Filtering

13

14  
15 Practical biomedical surfaces are usually multi-scale in nature, i.e. they are comprised of  
16 various topographic features with distinct scales. The cartilages also have the composite  
17 surface texture with multi-scale features. For instance, as shown in Fig. , a representative  
18 surface texture of Joint 3 clearly presents two dominant feature components with differing  
19 wavelengths. One is the large scale feature which has the wavelength larger than 50  $\mu\text{m}$  while  
20 the other component is the micro-scale feature which has the wavelength within the interval 1

1 ~ 20  $\mu\text{m}$ . As the large scale features are usually distributed in an instable way, in this study, the  
2 micro feature components is studied and used in wear assessment and prediction.

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Fig. 2. Representative 3D show of the surface texture of Joint 3.

To extract the micro-scale components, the S-L filtration defined in the new ISO standard [20] with areal Gaussian filter [21] was implemented. The S-filter is used to remove the small scale components (usually the high frequency noise) while the L-filter is aimed to remove the large scale components. Thus the S-L surface which only retains the interested surface texture information can be obtained.

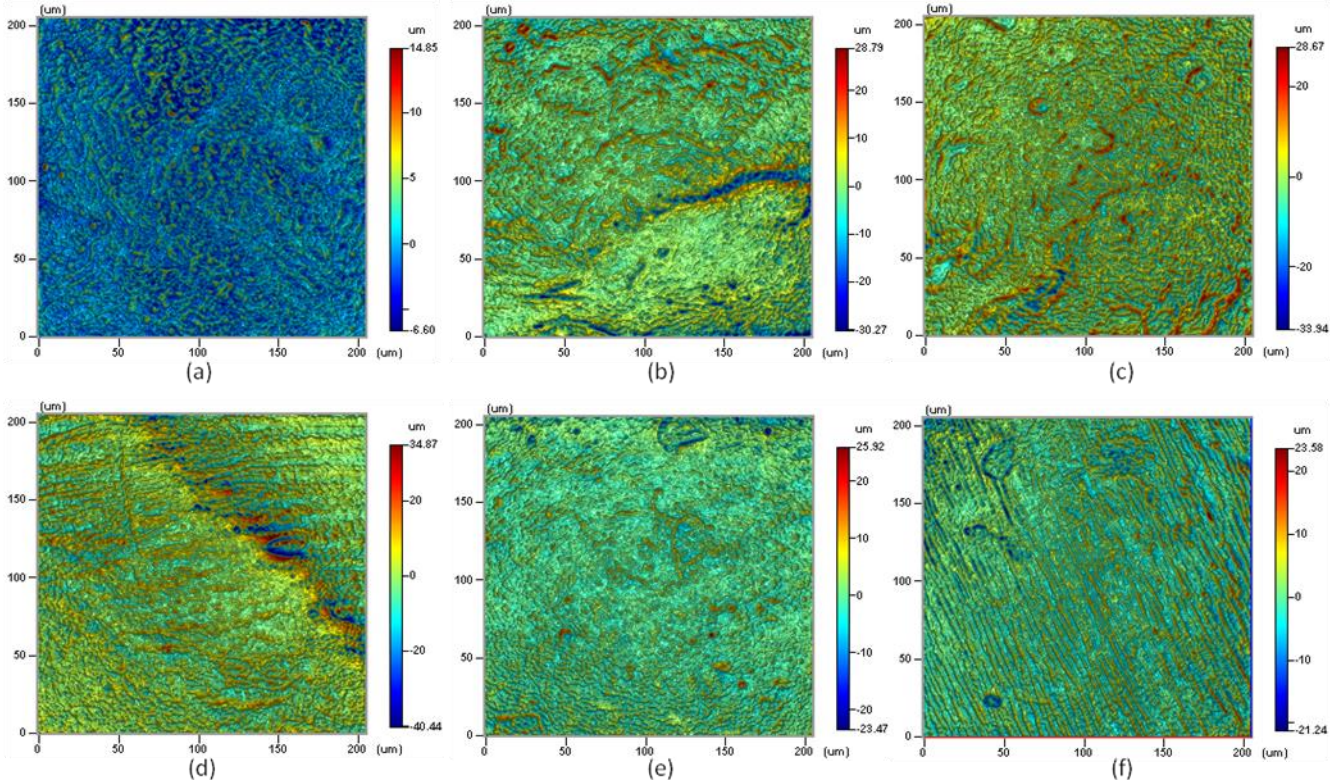
According to ISO 25178-3, the nesting indices of the L- and S- filter were selected in the following way. Because the 40x objective used in this study has the inherent sampling spacing 0.4  $\mu\text{m}$ , the nesting index of the S-filter was set to be five times of it at least, i.e. 2  $\mu\text{m}$ . Considering the F-operator and L-operator, levelling and the 800  $\mu\text{m}$  nesting index are suggested by [20] for the biomedical samples. However, in this study, the interested micro features have the scale ranging from 1 to 20  $\mu\text{m}$ . To remove all the unwanted lateral components, a compromising selection of the nesting indices based on the preferred empirical values [20] was determined as follows: 2.5  $\mu\text{m}$  for S-filtering, levelling for F-operator, and 25  $\mu\text{m}$  for L-filtering. The sampling conditions (sampling spacing and length) involved in the

1 surface scanning procedure, are listed in Table . Typical S-L surfaces of the six joints with  
 2 differing severity of wear conditions are shown in Figure 3.

3  
 4 Table 2 Sampling conditions and selection of the nesting indices of S-L filtration.

Sampling spacing	S-filter nesting index	Sampling length	F-Operator	L-filter nesting index
0.4 $\mu\text{m}$	2.5 $\mu\text{m}$	204 $\mu\text{m}$	Levelling	25 $\mu\text{m}$

5



6

7 Fig. 3. S-L AC surface textures of representative samples (a) Control; (b) Joint 1; (c) Joint 2; (d) Joint 3; (e) Joint  
 8 4; (f) Joint 5.

9

### 10 3.2 Numerical Surface Characterisation

11

12 After the filtration process described as above, the AC surfaces were analyzed using numerical  
 13 parameters. In the international standard ISO/FDIS 25178-2 [14], the parameter set so called  
 14 “field parameters” statistically calculate the continuous point cloud of areal surface texture and  
 15 preserve most traditional 3D surface texture parameters , such as  $Sq$  (root mean square surface  
 16 height) and  $Sdr$  (developed interfacial area ratio). A relative new set named as feature  
 17 parameters group, statistically processes a subset of pre-defined topographic features (e.g.



1 Maxwellian features: hills and valleys) which include *Spd* (density of peaks), *Spc* (peak mean  
 2 curvature) and other novel numerical parameters. Here, nearly all the defined 32 field and  
 3 feature parameters [14] were applied to study the AC surface features. The mean and standard  
 4 deviation of each parameter were calculated. Due to the large number of the numerical  
 5 parameters, only some of the results are shown in Table .

6  
 7 **3.3 Significance Test and Ten Critical Parameters**

8  
 9 Although nearly all the surface texture parameters were calculated, however, not all of them  
 10 have significant relationships with the AC wear conditions. To determine the significant  
 11 parameters to reveal the OA conditions, one-way analysis of variance (ANOVA) [22] was  
 12 carried out to test the significance of the parameters. The selection of critical numerical  
 13 parameters was based on the definitions of the parameters and their potential physical change  
 14 in the wear test.

15  
 16 The six groups from Control to Joint 5 of samples were tested here. For a numerical parameter,  
 17 if the six groups have no significant difference from each other, a statistic *F* is returned which  
 18 has a value below a critical value. Only those parameters which have significant difference  
 19 among the six groups are thought to be potentially useful. Under the significance  
 20 level  $\alpha = 0.05$ , 24 parameters out of 32 including 6 functional feature parameters have been  
 21 retained as significant ones because of their high *F* values. The means and standard deviations  
 22 of the 24 critical parameters are shown in Table .

23  
 24 Table 3 24 significant field parameters and feature parameters used in the study.

	Control		Joint 1		Joint 2		Joint 3		Joint 4		Joint 5		Total	
	Mea n	Std. Devi ation	Mea n	Std. Devi ation	Mea n	Std. Devi ation	Mea n	Std. Devi ation	Mea n	Std. Devi ation	Mea n	Std. Devi ation	Mea n	Std. Devi ation
Field parameters:														
<i>Sq</i> ( $\mu\text{m}$ )	2.34	0.98	3.91	1.52	4.60	1.34	4.93	1.22	2.62	0.98	2.67	1.42	3.60	1.57
<i>Ssk</i>	0.94	0.59	0.62	0.88	0.26	0.49	-0.12	0.16	0.62	0.45	-0.27	0.97	0.30	0.74
<i>Sp</i> ( $\mu\text{m}$ )	19.7 8	6.84	30.2 5	7.52	32.9 1	5.34	29.7 3	3.89	22.1 2	7.32	16.7 7	6.12	25.7 8	8.45
<i>Sv</i> ( $\mu\text{m}$ )	11.6 2	8.53	26.6 9	14.2 1	32.9 8	6.65	34.0 4	6.04	20.3 8	8.64	18.9 6	8.24	25.1 7	11.4 1
<i>Sz</i> ( $\mu\text{m}$ )	31.4 1	13.2 2	56.9 4	20.1 7	65.8 8	9.90	63.7 8	8.46	42.5 0	15.2 7	35.7 3	12.6 2	50.9 5	18.5 0



<i>Sa</i> ( $\mu\text{m}$ )	1.70	0.68	2.72	1.02	3.30	0.99	3.54	1.01	1.84	0.70	1.87	1.16	2.55	1.16
<i>Str</i>	0.73	0.25	0.67	0.18	0.64	0.17	0.51	0.22	0.75	0.20	0.37	0.22	0.60	0.23
<i>Sdq</i>	3.02	1.09	4.86	1.56	6.01	1.63	6.53	1.31	3.57	1.29	3.40	2.36	4.68	2.02
<i>Sdr</i> (%)	335.00	195.85	841.93	536.33	1244.66	596.74	1370.26	475.58	472.12	322.78	568.00	541.85	839.78	591.99
<i>Smc</i> ( $\mu\text{m}$ )	2.80	1.08	4.44	1.63	5.35	1.65	5.84	1.70	2.97	1.15	2.88	1.89	4.14	1.93
<i>Sxp</i> ( $\mu\text{m}$ )	3.97	2.45	7.54	4.35	8.67	3.31	9.73	2.38	4.59	2.10	5.59	3.07	6.89	3.58
<i>Spk</i> ( $\mu\text{m}$ )	3.87	1.44	6.26	1.68	7.08	2.23	6.74	1.31	4.12	1.59	3.43	1.93	5.37	2.21
<i>Sk</i> ( $\mu\text{m}$ )	4.52	1.68	6.87	2.31	8.88	2.80	9.58	3.62	4.92	2.14	5.02	3.70	6.78	3.35
<i>Svk</i> ( $\mu\text{m}$ )	2.42	2.04	5.44	3.56	5.91	2.20	6.96	1.49	3.21	1.61	3.90	2.11	4.82	2.66
<i>Vmp</i> ( $\mu\text{m}^3/\text{mm}^2$ )	1.94	7.43	3.12	7.89	3.51	1.12	3.34	6.29	2.10	8.44	1.80	9.72	2.70	1.08
	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0
	5	4	5	4	5	5	5	4	5	4	5	4	5	5
<i>Vmc</i> ( $\mu\text{m}^3/\text{mm}^2$ )	1.69	6.43	2.62	9.70	3.32	1.06	3.56	1.18	1.83	7.35	1.88	1.30	2.54	1.22
	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0
	6	5	6	5	6	6	6	6	6	5	6	6	6	6
<i>Vvc</i> ( $\mu\text{m}^3/\text{mm}^2$ )	2.71	1.00	4.20	1.37	5.06	1.57	5.44	1.61	2.83	1.06	2.65	1.78	3.90	1.78
	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0
	6	6	6	6	6	6	6	6	6	6	6	6	6	6
<i>Vvv</i> ( $\mu\text{m}^3/\text{mm}^2$ )	2.46	1.81	4.87	3.12	5.57	2.26	6.42	1.48	2.98	1.44	3.60	1.87	4.46	2.42
	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0	E+0
	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Feature parameters:														
<i>Spc</i> ( $1/\mu\text{m}$ )	7.42	1.64	12.3	2.61	14.9	2.88	16.3	2.09	10.4	2.73	7.66	4.18	11.8	4.25
			9	6	6		5		5				9	
<i>SIOz</i> ( $\mu\text{m}$ )	22.4	7.76	40.5	14.8	46.7	9.37	45.8	5.01	30.7	10.9	25.7	10.4	36.4	13.4
	0		2	4	0		4		7	2	6	7	7	5
<i>S5p</i> ( $\mu\text{m}$ )	14.3	3.80	21.4	4.94	23.3	4.50	21.1	1.73	15.9	4.92	11.8	4.43	18.3	5.84
	3		7		0		9		8		3		7	
<i>S5v</i> ( $\mu\text{m}$ )	8.06	5.40	19.0	10.9	23.4	6.02	24.6	4.37	14.7	6.79	13.9	6.85	18.1	8.61
			6	0	0		3		8		3		0	
<i>Sda</i> ( $\mu\text{m}^2$ )	0.14	0.02	0.19	0.06	0.14	0.06	0.14	0.06	0.17	0.10	0.67	0.83	0.25	0.39
<i>Sha</i> ( $\mu\text{m}^2$ )	0.10	0.05	0.13	0.04	0.13	0.03	0.13	0.05	0.16	0.11	0.99	1.29	0.28	0.61

1  
2 Although the 24 significant parameters are sensitive to the changes in the cartilage surface  
3 texture, they may have inherent similarity. For example, *Vmc*, core material volume of the  
4 texture and *Vvc*, void core volume of the texture surface, are defined from the dual character of  
5 surface texture volume [21]. It is therefore possible to further reduce the number of critical  
6 parameters through correlation analysis among the existing parameters, making it easy to deal  
7 with a small data set. The correlation coefficient analysis [18] has been considered. However,  
8 the method can only verify the linear correlation. Moreover, in this study, the 24 parameters  
9 will produce a large correlation matrix that is difficult to analyze. Thus an extraction of typical  
10 parameters based on parameter definitions was carried out in the combination with the  
11 correlation analysis.

12

1 According to [14], the field parameter set is divided into five groups based on their definitions.  
2 They are height, spatial, hybrid, functional and miscellaneous parameters. For instance,  $Sq$ , the  
3 root mean square height, is computed mainly based on the z-scale information, and thus it is a  
4 height parameter.  $Sdq$ , the root mean square gradient is computed based on both the z-scale and  
5 lateral information. Thus it is a hybrid parameter. Similarly, the functional parameters can also  
6 be divided into those classes which concern the peak height, valley height or core height,  
7 although most of them are extracted based the bearing curve [23]. Therefore, in this study,  
8 based on the parameter definitions, the remainder 24 parameters were classified into three  
9 groups and ten sub-groups as shown in Table . The correlation analysis was performed among  
10 the parameters which are in the same sub-groups to eliminate redundant parameters which may  
11 describe the same or similar surface characteristics. By observing the means of the six joints in  
12 Table , the rationality of the classification can be understood. For example, the valley height  
13 related parameters and the peak height related parameters have the maximum values on Joint 3  
14 and Joint 2 respectively. The most significant parameter in each class was selected based the  
15 produced  $F$  statistics in the one-way ANOVA which has been conducted as earlier. Thus, ten  
16 key parameters, which are  $S5p$ ,  $Sv$ ,  $Vvc$ ,  $Sz$ ,  $Sa$ ,  $Ssk$ ,  $Str$ ,  $Sha$ ,  $Sdq$ ,  $Spc$ , have been finally  
17 determined. Although, in the following correlation analysis as shown in

18

19 We are inclined to believe that the ten key parameters are typical based on their definition  
20 classification. However, two or more parameters from different groups are still probable to  
21 have correlations which are synchronously changing with OA progression. The correlations  
22 among the ten key parameters have been shown in Table 5. Each parameter has high  
23 correlations with some other ones, such as the one hundred percent correlation between  $Sa$ ,  
24 arithmetical mean height and  $Vvc$ , void core volume of the texture surface. It has indicated on a  
25 scale-limited AC surface, the void volume of the core zone is transforming together with the  
26 amplitude-related height texture properties. Although ten typical parameters are defined from  
27 different properties aspects, the high correlations across them still reveal the reduction  
28 potentiality of total critical parameters amount for OA prediction.

29

1 **Table** , there are some parameters such as *Sz* still have a strong linear relationship with others  
 2 such as *S5p*, *Sv* and *Vvc*, all the ten parameters have been retained as they belong to different  
 3 groups or sub-groups.

4

5 Table 4 Definition-based parameter classification of the 24 significant parameters. (\* Type 1 trend, \*\* Type 2  
 6 trend, \*\*\*Type 3 trend, \*\*\*\*Type 4 trend as shown in Figure 4 and explained later; highlights: the most  
 7 significant parameter in each group).

Height related						Spatial		Hybrid	
Peak height	Valley height	Core height	Total height	Mean height	Skewness	Aspect ratio	Feature size	Gradient	Curvature
<i>Sp</i> **	<i>Sv</i> *	<i>Sk</i> *	<i>Sz</i> **	<i>Sq</i> *	<i>Ssk</i> ***	<i>Str</i> ***	<i>Sda</i> ****	<i>Sdq</i> *	<i>Spc</i> *
<i>Spk</i> **	<i>Svk</i> *	<i>Vmc</i> *	<i>S10z</i> **	<i>Sa</i> *			<i>Sha</i> ****	<i>Sdr</i> *	
<i>Smc</i> *	<i>Sxp</i> *	<i>Vvc</i> *							
<i>Vmp</i> **	<i>Vvv</i> *								
<i>S5p</i> **	<i>S5v</i> *								

8

9

10 We are inclined to believe that the ten key parameters are typical based on their definition  
 11 classification. However, two or more parameters from different groups are still probable to  
 12 have correlations which are synchronously changing with OA progression. The correlations  
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 15 arithmetical mean height and *Vvc*, void core volume of the texture surface. It has indicated on a  
 16 scale-limited AC surface, the void volume of the core zone is transforming together with the  
 17 amplitude-related height texture properties. Although ten typical parameters are defined from  
 18 different properties aspects, the high correlations across them still reveal the reduction  
 19 potentiality of total critical parameters amount for OA prediction.

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Table 5 Correlation matrix of the ten typical parameters.

Correlations	<i>S5p</i>	<i>Sv</i>	<i>Vvc</i>	<i>Sz</i>	<i>Sa</i>	<i>Ssk</i>	<i>Str</i>	<i>Sha</i>	<i>Sdq</i>	<i>Spc</i>
<i>S5p</i>	1.00									
<i>Sv</i>	0.86	1.00								
<i>Vvc</i>	0.91	0.94	1.00							
<i>Sz</i>	0.95	0.98	0.96	1.00						
<i>Sa</i>	0.89	0.96	1.00	0.96	1.00					
<i>Ssk</i>	0.01	-0.49	-0.33	-0.29	-0.40	1.00				
<i>Str</i>	0.24	-0.21	-0.10	-0.03	-0.18	0.93	1.00			
<i>Sha</i>	-0.65	-0.27	-0.45	-0.44	-0.38	-0.65	-0.81	1.00		

<i>Sdq</i>	0.88	0.97	0.99	0.97	1.00	-0.41	-0.17	-0.38	1.00	
<i>Spc</i>	0.91	0.96	0.97	0.97	0.96	-0.30	-0.02	-0.50	0.98	1.00

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### 3.4 Four Typical Trends

After selecting the ten key parameters, the change in the trends of the surface texture parameters were analyzed to reveal the progressively worse wear conditions. Some predecessors have contributed on the trend analysis of the size parameters of the wear particles. In their work [11, 18], a parabolic trend have been confirmed that the length and area of wear particles have an increase until Joint 4 where the maximum measurement values are achieved, and further a decrease. In this study of the surface texture parameters, four basic types of trends have been observed.

Seven of the ten key parameters, that is, *S5p*, *Sz*, *Sv*, *Vvc*, *Sa*, *Sdq* and *Spc*, exhibit a parabolic trend with the wear severity of the AC as illustrated in Figure 4(a). The former two have the maximum values at Joint 2 while the others have the maximum values at Joint 3. In Fig. (a), two typical presentations of the parabolic trend (*S5p* and *Sv*) are shown which are noted as then trend Type 1 and Type 2. However, the remainder three parameters exhibit miscellaneous changing trends. Trends of *Ssk* and *Str* fall into three monotonous intervals. They decline from Control to Joint 3, followed by an increase until Joint 4, and finally a decrease to Joint 5 as shown in Figure 4(b) Type 3. Different to *Ssk* and *Str* (Type 3 trend) *Sha* seems to have presented a progressive climbing process though the ascending speed of the first four processes is very slow. This miscellaneous trend is shown in Fig. (b), named as trend Type 4.

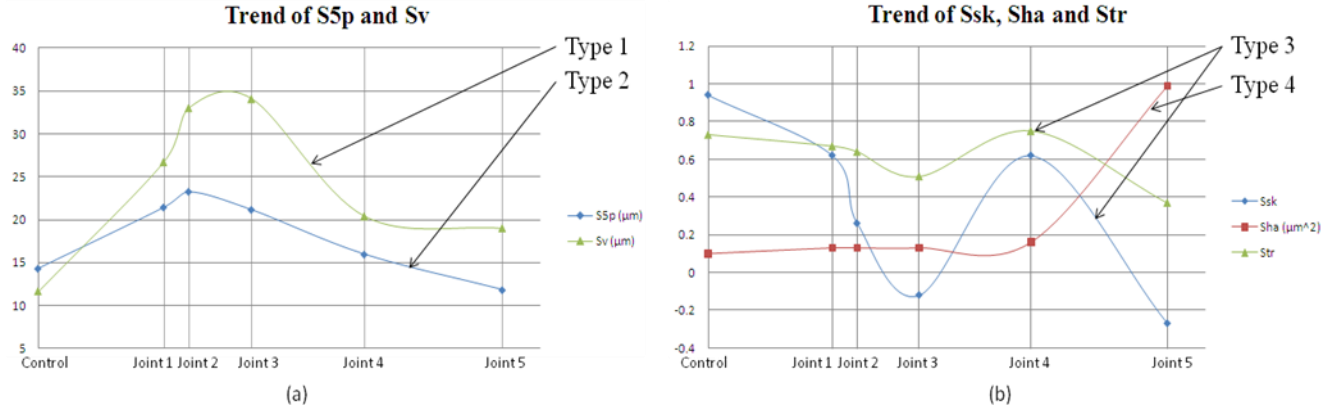


Fig. 4. Trends of typical surface texture parameters.

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2 Reversely considering all the 24 significant parameters, it can be found that all the trends of  
3 them fall into one of the four typical trend types. In Table , each parameter has been marked  
4 relating to the corresponding trend types. It can be found that all the valley height, core height,  
5 mean height related parameter and hybrid parameters have the Type 1 trend, and most of the  
6 peak height and total height related parameters show the Type 2 trend in this study. The trends  
7 of skewness and aspect ratio related parameters fall into the shape of Type 3 while the trends of  
8 most of the feature size related parameters such as *Sda*, *Sha*, follow Type 4 trend.

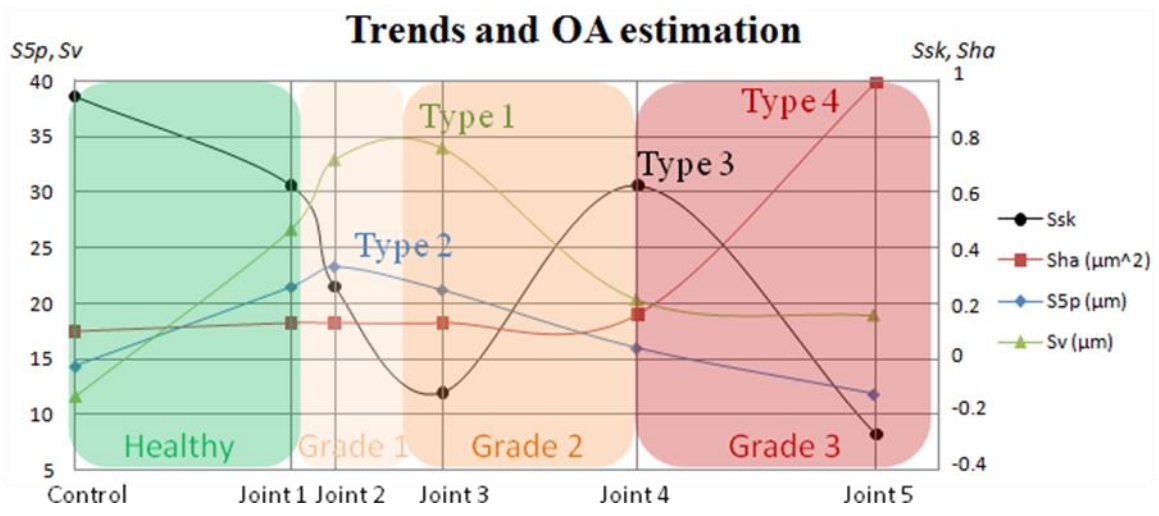
#### 9 10 11 *4. Discussion*

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13 In this study, the field and feature parameters defined in ISO/FDIS 25178-2 have been  
14 employed to study the surface texture of cartilage samples collected from sheep knee joints.  
15 Six groups of AC samples were collected from health knee joint to OA degrees 1, 2 and 3. It is  
16 the first time that the feature parameters have been applied together with the field parameters to  
17 the AC wear studies.

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19 After the one way ANOVA analysis, 24 parameters out of total 32 have returned a high F value  
20 showing significance with six AC groups surface change. The results reveal that most  
21 parameters in the two sets are sensitive to cartilage surface change with the wear degrees  
22 progress. The feature parameters, developed to study the functional properties of surface, are  
23 the first time implemented in AC surface texture analysis. Six of nine feature parameters have  
24 shown significance with AC surface wear development and three of them have been selected as  
25 key parameters. The application of the feature parameters in wear progression evaluation has  
26 offered a novel approach to investigate the functional properties of contact cartilage surface  
27 area within knee joints. This study has shown that the selected field parameters and newly  
28 defined feature parameters reveal the cartilage surface texture changes and thus have potential  
29 to be used for OA assessment.

1 The past research [18] with the same experiment design has revealed the variation of the OA  
 2 degrees in the wear test by analyzing the particle geometries. Based on that work, the suspected  
 3 OA degrees together with the four typical trends of surface texture parameters are presented in  
 4 Fig 5. The trend of Type 1 and Type 2, which covers nearly all the height related parameters  
 5 (except  $Ssk$ ) and the hybrid parameters, has a slow climbing in the healthy wear interval, and  
 6 then followed by a fast ascent during the grade 1 osteoarthritis. When the OA gets worsen to  
 7 grade 2, the value of the two types of parameters starts to decline. Finally during the grade 3  
 8 osteoarthritis, they decrease further with a relatively lower rate than before. Different to Types  
 9 1 and 2 trend, for the Type 3 trend ( $Ssk$  and  $Str$ ), it has a slow decay in the duration of the  
 10 healthy wear, and then followed by a significant drop in the grade 1 osteoarthritis. During the  
 11 OA grade 2, it starts moving to the opposite direction; and finally in the OA grade 3 duration, it  
 12 decreases its value again. As for the Type 4 trend ( $Sda$  and  $Sha$ ), no clear variation trend can be  
 13 observed in the early stages until the osteoarthritis grade 3 is arrived where a distinct elevation  
 14 is formed.

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Fig. 5. The four typical trends of surface texture parameters and the suspected OA degrees.

19 Unlike most engineering materials articular cartilage is an inhomogeneous material. The layer  
 20 structured AC has varying physical and biomechanical properties including wear resistance  
 21 from superficial lipid film, intermediate collagen network, to calcified subchondral bone [6].  
 22 Therefore, it is difficult to perform a one-way linear plotting using the numerical analyzed

1 data. Seven of total ten key parameters exhibit parabolic trend Types 1 and 2 in Figure 5  
2 which is in accordance with previous morphology studies for OA assessment [11, 18]. The  
3 versified trend include that the height related defined  $S_v$  and  $S_z$  increase from the control joint  
4 to Joint 2 and then decrease from Joint 2 corresponding to OA degree 1 or Joint 3 of OA  
5 degree 2.

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7 One possible reason for the phenomena is that until the wear testing cycle reaches 17,000 of  
8 Joint 3, soft tissue on the top layer of the cartilage continuously becomes rougher. This change  
9 is revealed by the trend of the  $S_a$ , arithmetical mean height. It rises from 1.7 of Control Joint to  
10 3.54 of Joint 3. As the wear process progresses, the roughened lay is removed and smoothed  
11 with the underneath, harder structure exposed to wear. The decreases of the  $S_a$  value from Joint  
12 3 to 1.87 microns of Joint 5 may be an evidence of the above explanation. The parabolic trend  
13 of most height and height related parameters reveals and confirms the wear process described  
14 above.

15  
16 The application of the feature parameters has allowed a new, alternative way to the  
17 investigation of the cartilage surface changes and wear conditions from a different angle. This  
18 study has shown that curvature related  $S_{pc}$ , the arithmetic mean of the principle curvatures of  
19 peaks, and peak height related  $S_{5p}$  defined as the average value of the heights of the five peaks  
20 with largest global peak height within a definition area, two key feature parameters follow the  
21 parabolic distribution of Types 1 and 2 trend in Figure 5 in relation to the cartilage health  
22 conditions. Their values increase first and then decrease, in line with the results of the field  
23 parameters described previously in Types 1 and 2 trend. Interestingly, another feature  
24 parameter,  $S_{ha}$ , defined as the average area of hills connected to the edge, stays steady until  
25 Joint 4 and then rapidly increases to Joint 5 as shown in trend Type 4 in Figure 5. It indicates  
26 that the AC contact area between femial and tibial end remains almost constant from Control  
27 joint to OA grade 2, and then increases as the OA condition further worsens. The application  
28 of the feature parameters in wear progression evaluation has offered a new approach to  
29 investigate the functional properties of contact cartilage surface area within knee joint. It is  
30 clear that with the assistance of the feature parameters, further study needs to be conducted to  
31 seek an insight into the wear process and cartilage surface changes.



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To examine the stability of the field and feature parameters for knee joint OA assessment, more numerical analysis data are necessary from further tests. Statistical analysis for more cartilage samples could examine the reliability of the key parameters function and investigate the correlation between the field and feature parameters and conventional surface morphology parameters. Furthermore, the wear stimulator cycles or impulse load could be varied to inspect the parabolic trend change under longer wear testing time.

*5. Conclusion*

This study has used the field and feature parameters from ISO/FDIS 25178 for analyzing cartilage surface texture changes under the degrees of wear conditions varying from normal condition to OA grade 3. Seven field parameters and three feature parameters have been selected as critical numerical descriptors to characterise the surface evolution in the study. The trend of the field parameters is similar to what has been reported in the previous studies.

This is the first time the feature parameters are used to investigate the cartilage surfaces and their modification with the wear conditions. Majority of nine innovatively developed feature parameters have shown sensitive to the cartilage surface texture changes. This approach offers a new approach for studying joint functional performance in wear progression. Complied with previous results, majority of the parameters results have shown a parabolic distribution and the reasons behind this need to be further investigated. The overall performance of the field and feature parameters has indicated that there is a great potential to further develop the parameters for early OA diagnosis.

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