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Numerical analysis of cartilage surfaces for Osteoarthritis diagnosis using field and feature parameters

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Abstract

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

Keywords: Field and feature parameters; Articular cartilage; Surface texture; Numerical analysis; Osteoarthritis

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1. Introduction

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

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

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

Field and feature parameters are two defined sets of surface texture parameters compiled by ISO/FDIS 25178-2 [14]. The field parameters apply statistics to the continuous point cloud of areal surface texture data, which inherits the majority of the conventional 3D surface texture parameters. The feature parameters apply statistics from a subset of pre-defined topographic features [15]. This characterisation method adopts feature characterisation techniques, and it can prune out those instable features [16], and it is expected to be more stable than the conventional surface texture parameters.

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

2. Wear Testing and Image Acquisition

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

2.1 Wear Test

Three 11 months merino sheep assumed being in health joint conditions was used in this study. All the sheep were anesthetized and painless killed under strict approval from Animal Ethics Committee, James Cook University (JCU), Australia. Total six joints gathered from hind legs were fixed on a wear simulator set up in the mechanical engineering laboratory at JCU. The wear tester [18] could simulate normal walking motion with the assistance of an airbag which was attached to offer variable loading to the testing joints. One joint was chosen as control joints and the other five were tested in different time spans to produce specimens with OA grade 1 to 3. Testing conditions of the joints are shown in Table 1.

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

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

2.2 Image Acquisition and Imaging Process

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

Under LSCM 40x objective lens and 0.66mw to 0.88mw 514nm Argon laser, a 512*512 pixels images stack was gained with a 0.2 μm z-direction step size scanning. Then the images stacks were processed using image processing codes developed in Matlab 6.5 package to generate a Height Encode Image (HEI) containing 3D surface information of the AC samples, followed by filtering and numerical analysis with field and feature parameters, which will be presented in the following separate section. An image of Joint 2 cartilage surface and a Joint 4 visually enhanced HEI image are in shown Figure 1.

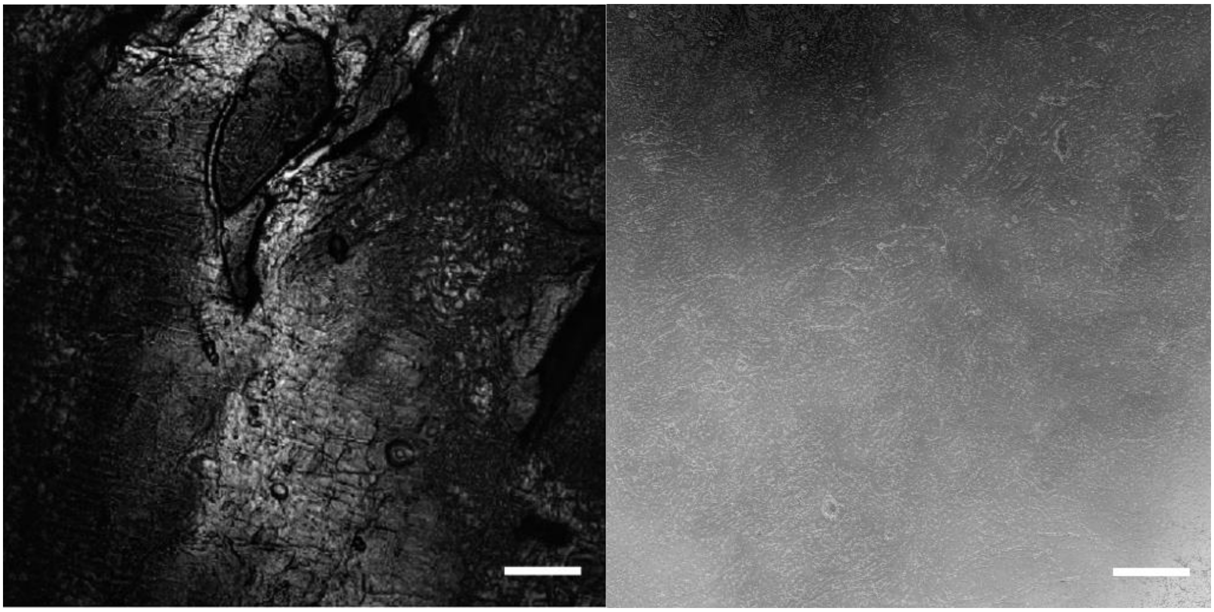

Fig.1. (a) 40x Joint 2 cartilage surface image; (b) 40x Joint 4 visually enhanced HEI image； scale bar=50 μm.

3. Numerical Analysis and Results

3.1 Filtering

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

~ 20 μm. As the large scale features are usually distributed in an instable way, in this study, the micro feature components is studied and used in wear assessment and prediction.

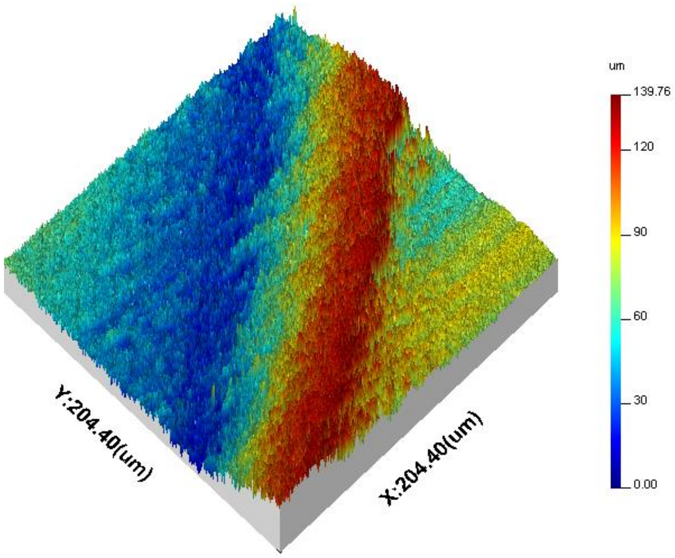

Fig. 2. Representative 3D show of the surface texture of Joint 3.

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 μm, the nesting index of the S-filter was set to be five times of it at least, i.e. 2 μm. Considering the F-operator and L-operator, levelling and the 800 μm 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 μm. 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 μm for S-filtering, levelling for F-operator, and 25 μm for L-filtering. The sampling conditions (sampling spacing and length) involved in the surface scanning procedure, are listed in Table . Typical S-L surfaces of the six joints with differing severity of wear conditions are shown in Figure 3.

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 μm	2.5 μm	204 μm	Levelling	25 μm

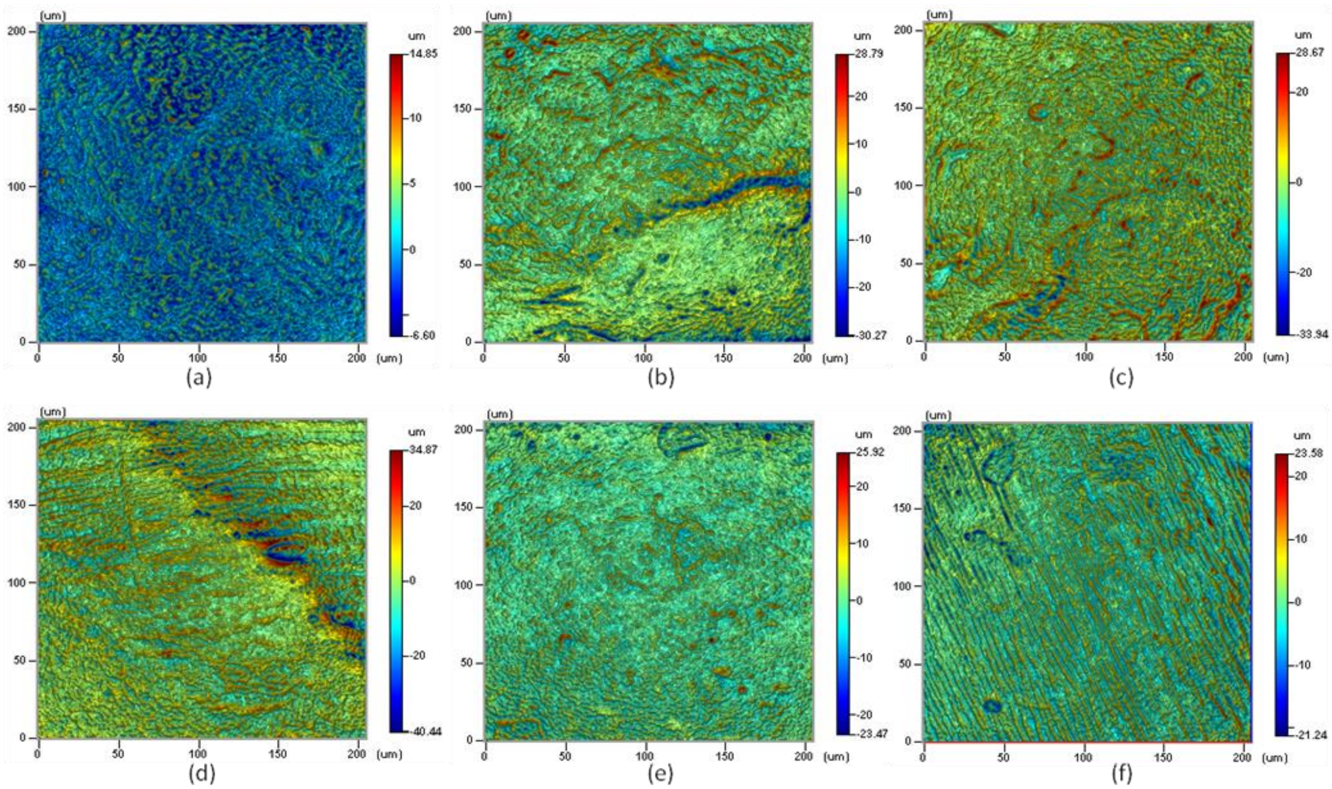

Fig. 3. S-L AC surface textures of representative samples (a) Control; (b) Joint 1; (c) Joint 2; (d) Joint 3; (e) Joint 4; (f) Joint 5.

3.2 Numerical Surface Characterisation

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

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

3.3 Significance Test and Ten Critical Parameters

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

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

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	
	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
Field parameters:														
Sq (μm)	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
Ssk	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
Sp (μm)	19.78	6.84	30.25	7.52	32.91	5.34	29.73	3.89	22.12	7.32	16.77	6.12	25.78	8.45
Sv (μm)	11.62	8.53	26.69	14.21	32.98	6.65	34.04	6.04	20.38	8.64	18.96	8.24	25.17	11.41
Sz (μm)	31.41	13.22	56.94	20.17	65.88	9.90	63.78	8.46	42.50	15.27	35.73	12.62	50.95	18.50

Sa (μm)	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
Str	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
Sdq	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
Sdr (%)	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
Smc (μm)	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
Sxp (μm)	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
Spk (μm)	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
Sk (μm)	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
Svk (μm)	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
Vmp ($\mu m^3/mm^2$)	1.94E+05	7.43E+04	3.12E+05	7.89E+04	3.51E+05	1.12E+05	3.34E+05	6.29E+04	2.10E+05	8.44E+04	1.80E+05	9.72E+04	2.70E+05	1.08E+05
Vmc ($\mu m^3/mm^2$)	1.69E+06	6.43E+05	2.62E+06	9.70E+05	3.32E+06	1.06E+06	3.56E+06	1.18E+06	1.83E+06	7.35E+05	1.88E+06	1.30E+06	2.54E+06	1.22E+06
Vvc ($\mu m^3/mm^2$)	2.71E+06	1.00E+06	4.20E+06	1.37E+06	5.06E+06	1.57E+06	5.44E+06	1.61E+06	2.83E+06	1.06E+06	2.65E+06	1.78E+06	3.90E+06	1.78E+06
Vvv ($\mu m^3/mm^2$)	2.46E+05	1.81E+05	4.87E+05	3.12E+05	5.57E+05	2.26E+05	6.42E+05	1.48E+05	2.98E+05	1.44E+05	3.60E+05	1.87E+05	4.46E+05	2.42E+05
Feature parameters:														
Spc (1/μm)	7.42	1.64	12.39	2.61	14.96	2.88	16.35	2.09	10.45	2.73	7.66	4.18	11.89	4.25
S10z (μm)	22.40	7.76	40.52	14.84	46.70	9.37	45.84	5.01	30.77	10.92	25.76	10.47	36.47	13.45
S5p (μm)	14.33	3.80	21.47	4.94	23.30	4.50	21.19	1.73	15.98	4.92	11.83	4.43	18.37	5.84
S5v (μm)	8.06	5.40	19.06	10.90	23.40	6.02	24.63	4.37	14.78	6.79	13.93	6.85	18.10	8.61
Sda (μm^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
Sha (μm^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

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

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

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

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

Table 4 Definition-based parameter classification of the 24 significant parameters. (* Type 1 trend, ** Type 2 trend, ***Type 3 trend, ****Type 4 trend as shown in Figure 4 and explained later; highlights: the most 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
*Sp***	*Sv**	*Sk**	*Sz***	*Sq**	*Ssk****	*Str****	*Sda*****	*Sdq**	*Spc**
*Spk***	*Svk**	*Vmc**	*S10z***	*Sa**			*Sha*****	*Sdr**	
*Smc**	*Sxp**	*Vvc**							
*Vmp***	*Vvv**								
S5p **	*S5v**								

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

Table 5 Correlation matrix of the ten typical parameters.

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

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

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.

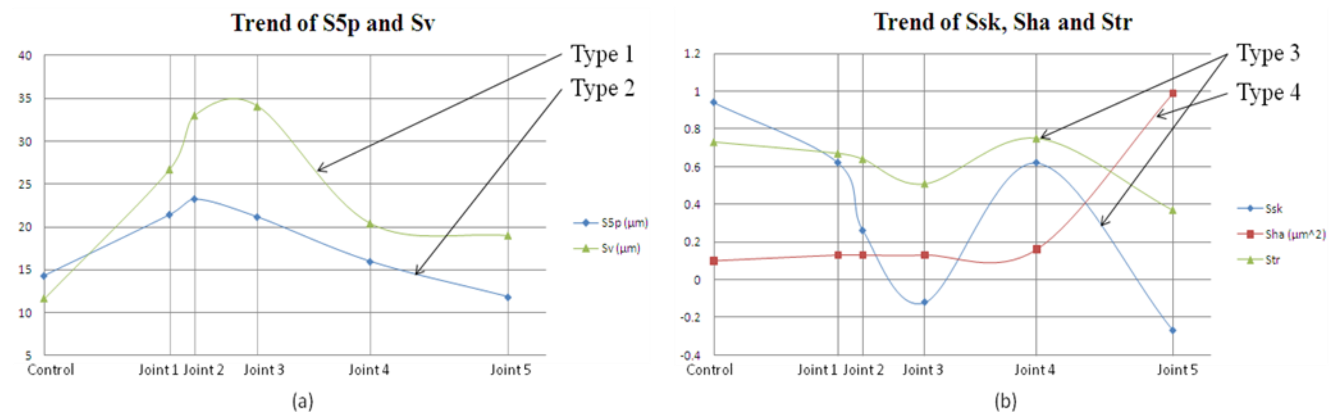

Fig. 4. Trends of typical surface texture parameters.

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

4. Discussion

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

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

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

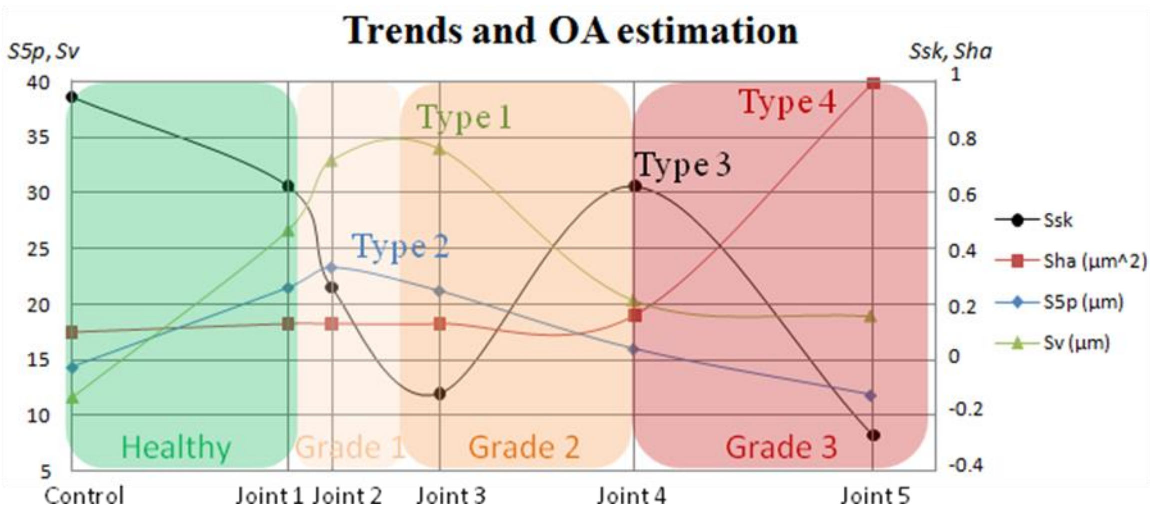

Fig. 5. The four typical trends of surface texture parameters and the suspected OA degrees.

Unlike most engineering materials articular cartilage is an inhomogeneous material. The layer structured AC has varying physical and biomechanical properties including wear resistance from superficial lipid film, intermediate collagen network, to calcified subchondral bone [6]. Therefore, it is difficult to perform a one-way linear plotting using the numerical analyzed data. Seven of total ten key parameters exhibit parabolic trend Types 1 and 2 in Figure 5 which is in accordance with previous morphology studies for OA assessment [11, 18]. The versified trend include that the height related defined *Sv* and *Sz* increase from the control joint to Joint 2 and then decrease from Joint 2 corresponding to OA degree 1 or Joint 3 of OA degree 2.

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

The application of the feature parameters has allowed a new, alternative way to the investigation of the cartilage surface changes and wear conditions from a different angle. This study has shown that curvature related *Spc*, the arithmetic mean of the principle curvatures of peaks, and peak height related *S5p* defined as the average value of the heights of the five peaks with largest global peak height within a definition area, two key feature parameters follow the parabolic distribution of Types 1 and 2 trend in Figure 5 in relation to the cartilage health conditions. Their values increase first and then decrease, in line with the results of the field parameters described previously in Types 1 and 2 trend. Interestingly, another feature parameter, *Sha*, defined as the average area of hills connected to the edge, stays steady until Joint 4 and then rapidly increases to Joint 5 as shown in trend Type 4 in Figure 5. It indicates that the AC contact area between femial and tibal end remains almost constant from Control joint to OA grade 2, and then increases as the OA condition further worsens. The application of the feature parameters in wear progression evaluation has offered a new approach to investigate the functional properties of contact cartilage surface area within knee joint. It is clear that with the assistance of the feature parameters, further study needs to be conducted to seek an insight into the wear process and cartilage surface changes.

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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