Quantitative assessment of hip osteoarthritis based on image texture analysis

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ABSTRACT. A non-invasive method was developed to investigate the potential capacity of digital image texture analysis in evaluating the severity of hip osteoarthritis (OA) and in monitoring its progression. 19 textural features evaluating patterns of pixel intensity fluctuations were extracted from 64 images of radiographic hip joint spaces (HJS), corresponding to 32 patients with verified unilateral or bilateral OA. Images were enhanced employing custom developed software for the delineation of the articular margins on digitized pelvic radiographs. The severity of OA for each patient was assessed by expert orthopaedists employing the Kellgren and Lawrence (KL) scale. Additionally, an index expressing HJS-narrowing was computed considering patients from the unilateral OA-group. A textural feature that quantified pixel distribution non-uniformity (grey level non-uniformity, GLNU) demonstrated the strongest correlation with the HJS-narrowing index among all extracted features and utilized in further analysis. Classification rules employing GLNU feature were introduced to characterize a hip as normal or osteoarthritic and to assign it to one of three severity categories, formed in accordance with the KL scale. Application of the proposed rules resulted in relatively high classification accuracies in characterizing a hip as normal or osteoarthritic (90.6%) and in assigning it to the correct KL scale category (88.9%). Furthermore, the strong correlation between the HJS-narrowing index and the pathological GLNU ($r=-0.9$, $p<0.001$) was utilized to provide percentages quantifying hip OA-severity. Texture analysis may contribute in the quantitative assessment of OA-severity, in the monitoring of OA-progression and in the evaluation of a chondroprotective therapy.

Received 13 December 2004
Revised 8 June 2005
Accepted 1 July 2005

DOI: 10.1259/bjr/87956832

Osteoarthritis (OA) is a common joint disease that causes degenerative alterations in the hip as well as other joints [1]. Characteristic radiological manifestation of hip OA includes irregular superolateral, superior or superomedial hip joint space (HJS) narrowing, femoral and acetabular subchondral bone sclerosis, development of marginal osteophytes, as well as femoral and acetabular subchondral cysts formation [2].

Plain film radiography remains the most prevalent imaging modality for diagnosis of hip OA in clinical routine, despite its limited sensitivity compared with innovative imaging techniques, such as CT and MRI [3]. Radiographic assessment of hip OA comprises diagnosis, evaluation of severity, and monitoring of progression of structural alterations related to the disease [4]. A number of qualitative or semi-quantitative grading systems have been proposed for assessing hip OA [5–8], with the Kellgren and Lawrence (KL) grading scale [5] being considered the gold standard despite its deficiencies [9]. A reliable index for monitoring hip OA progression on pelvic radiographs is the progression of HJS-narrowing [6, 10], which may be estimated either manually [11, 12], or by computerized methods [13–15]. The latter are more sensitive, accurate, reproducible, and thus more reliable [16].

Texture analysis refers to algorithms developed to quantify image texture information that may, or may not, be perceived visually [17]. Although texture analysis has been previously employed in examining knee OA by computer processing of radiographic images [18, 19], hip OA has only been investigated in one study by computer analysis (fractal geometry) of digitized histological sections from the femoral head [20]. So far, the quantitative assessment of hip OA has mainly relied on measurements of HJS-width or HJS-area performed on pelvic radiographs [11–15]. To our knowledge, the textural properties of radiographic HJS in OA hips, as well as the capability of computer based radiographic texture analysis in evaluating the severity of hip OA have not been previously investigated.

In the present study, a non-invasive method was developed for analysing the structure of HJS from pelvic radiographs and for evaluating the severity of hip OA,

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The first author was supported by a grant from the State Scholarship Foundation (SSF), Greece.

employing computerized texture analysis. In particular, (i) textural features were extracted from the outlined region of each radiographic HJS, (ii) textural-feature thresholds, bearing good correlation to KL scale severity grades, were established for grading OA automatically, and (iii) an index was introduced for evaluating OA-severity.

Methods and materials

Radiographs and patients

32 anteroposterior pelvic radiographs of standing weight-bearing osteoarthritic patients were collected, giving in total 64 hip joint images. All radiographs were retrieved from the medical records of individuals who were candidates for total hip arthroplasty at the Department of Orthopaedics in our Hospital. From the total number of patients, 18 were verified for unilateral and 14 for bilateral hip OA. Patients' ages ranged between 49 years and 83 years with a mean age of 66.7 years. The American College of Rheumatology criteria [21] were used for OA diagnosis.

All pelvic radiographs were obtained using a Siemens X-ray unit (Polydoros 50; Siemens, Erlangen, Germany). Radiographic protocol comprised alignment of the X-ray beam 2 cm above the pubic symphysis, a focus–film distance of 100 cm, tube voltage between 70 kVp and 80 kVp, and use of a fast screen and film cassette (30 cm $\times$ 40 cm). Digitization of radiographs was performed at 12 bits (4096 grey levels) and 146 ppi (5.8 pixels mm^{-1}) spatial resolution, using a laser digitizer for medical applications (Lumiscan 75; Lumisys, Sunnyvale, CA) [22]. Digitizer performance was evaluated employing a quality control protocol [23]. All radiographs fulfilled a specific criterion concerning safeguard against variations in hip rotation, introduced by the experienced orthopaedists. According to this criterion, the difference between the widths of projected lesser trochanters on each radiograph should not exceed 8 mm. Measurements on radiographs were performed by custom developed software [24–26].

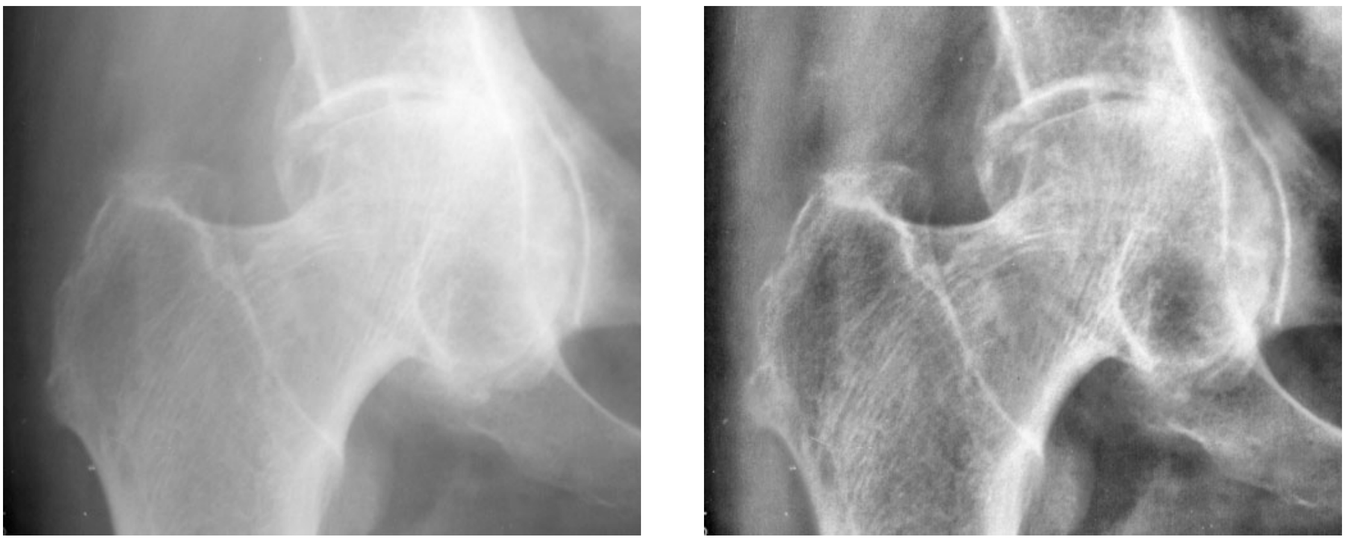
Three experienced orthopaedists assessed the severity of OA employing the KL grading scale. The KL scale defines five categories of OA-severity (0–4), with KL grades $\geqslant$2 corresponding to osteoarthritic pathology [5]. Based on the KL scale, patients were grouped into three major OA-severity categories: Normal/Doubtful (KL=0, 1), Mild/Moderate (KL=2, 3), and Severe (KL=4). Accordingly, 18 unilateral-OA patients were assigned to Normal/Doubtful category, 9 to Mild/Moderate and 9 to Severe. The corresponding numbers for the bilateral patients were 0/7/21.

Radiograph enhancement

Pelvic radiographs were first processed by means of custom developed software based on the contrast-limited adaptive histogram equalization (CLAHE) method [27], in order to emphasise the articular margins of the hip joint. The CLAHE method partitioned the images into contextual non-overlapping regions. Within each region the local histogram was obtained, clipped to a specific limit and then histogram equalization was performed within the region. Figure 1 shows a digitized radiograph enhanced by the implementation of CLAHE algorithm. On each enhanced radiograph two regions of interest (ROIs), one from the osteoarthritic HJS and one from the contralateral normal HJS, were manually outlined by three experienced orthopaedists, in accordance with the method proposed by Conrozier et al [13]. As shown in Figure 2, each ROI was defined within an acute angle determined by the patient's standard anatomical landmarks.

Texture analysis of radiographic hip joint space

A total of 19 textural features were extracted from each segmented HJS-ROI (see Figure 3), utilizing custom



(a) (b)

Figure 1. Example of (a) an original and (b) the corresponding processed digitized radiograph with the contrast-limited adaptive histogram equalization enhancement algorithm.

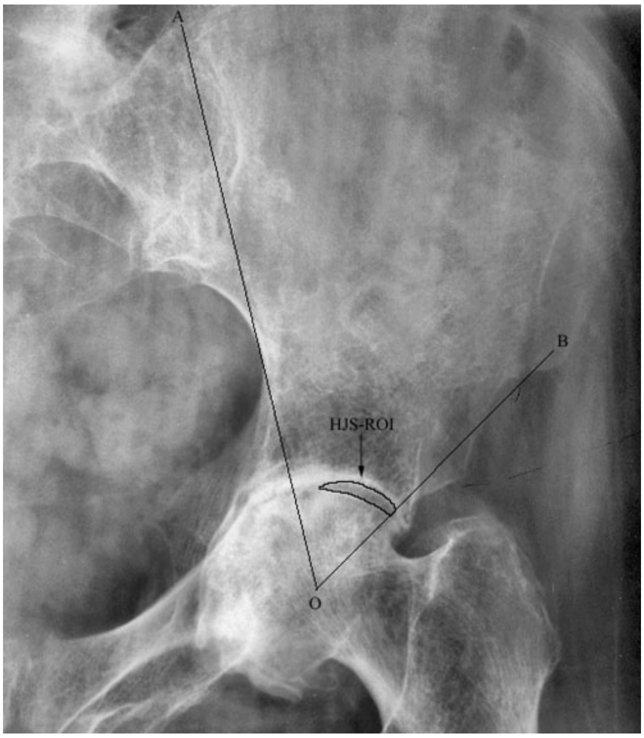


Figure 2. Hip joint space-region of interest (HJS-ROI) delineation within AOB. A: highest point of the homolateral sacral wing, O: centre of the femoral head, and B: lateral rim of the acetabulum.

Figure 3. Grey scale image of hip joint space region of interest (ROI) delineated in Figure 2.

developed algorithms. (i) Four textural features were computed from the ROI's grey level histogram [28], (ii) 10 from the ROI's grey level co-occurrence matrix [29] and (iii) five using the ROI's grey level run-length matrix [30].

Textural feature selection

From the extracted 19 textural features, selection was based on their correlation to an index evaluated for each of the unilateral OA-group patient, employing Equation (1):

$$\mathrm{HJS-narrowing} = \frac{\mathrm{HJSA_{normal}} - \mathrm{HJSA_{path}}}{\mathrm{HJSA_{normal}}} \times 100 \qquad (1)$$

where $\mathrm{HJSA_{normal}}$ and $\mathrm{HJSA_{path}}$ express the number of pixels corresponding to the manually segmented contralateral normal and osteoarthritic HJS-ROIs, respectively. We have introduced this index, since it quantifies OA-severity by expressing the HJS-narrowing as a percentage of HJS-area difference between the osteoarthritic and contralateral normal HJS. This index is expected to give zero value in case of normal joints, since differences in hip joint spaces have been shown to be negligible in normal individuals [13, 31].

The validity of the proposed HJS-narrowing index was evaluated by examining its correlation with the KL scale, since the latter is considered to be the gold standard for OA-severity assessment. Analysis of HJS-narrowing index performance compared with KL scale is provided in a corresponding paragraph of the Results and Discussion section.

Statistical analysis

The existence of statistically significant differences between osteoarthritic and contralateral normal hips was investigated in the patients of the unilateral OA-group. Differences in HJS-area or in textural features were examined by means of the two-tailed student's paired *t*-test. To assess the relationship between the HJS-narrowing index and each textural feature extracted from osteoarthritic HJS-ROIs, the Pearson's correlation coefficient was used. To evaluate intraobserver and interobserver reproducibility concerning HJS-area measurements and GLNU calculated values, the coefficient of variation (CV) was used [32]. Accordingly, all radiographs were separately evaluated by each one of the experienced orthopaedists twice, with about a 1 month interval between evaluations. Evaluation scores were used to calculate the CV, which provides (*e.g.* see Conrozier et al [13]) an assessment of interobserver or intraobserver reproducibility; low coefficient values correspond to high degree of reproducibility. Referring to measured quantities, normality of their distributions was assessed by means of the Lilliefors test [33]. For non-gaussian distributions, a logarithmic transformation ($\log_{10}$) was applied to corresponding data. Matlab Statistics Toolbox and Matlab Curve Fitting toolbox (The MathWorks Inc., Natick, USA) were used for statistical and regression analysis.

Results and discussion

In a digital image, texture is characterized by intensity properties (tone) and spatial inter-relationships (structure) of image pixels, depicting spatial distribution of grey level variations in the image [29, 34]. In a digitized plain radiograph, a two-dimensional spatial distribution of grey-level variation is formed by projecting on a two-dimensional level the three-dimensional spatial distribution of the X-ray attenuation coefficients [17]. In the present paper, textural properties of each analysed radiographic HJS-ROI were attributed to X-ray attenuation, due to superimposed three-dimensional anatomical structures of articular cartilage, posterior acetabular wall and iliac bone. Therefore, the analysed radiographic ROI comprises of either osteoarthritic and/or normal superimposed anatomical components. Consequently, digital image texture analysis attempts to assess the existence and/or severity of structural alterations related to OA.

In patients with unilateral hip OA, statistical analysis revealed the existence of statistically significant differences in 11 (out of 19) textural features values between osteoarthritic and contralateral normal HJS-ROIs. Mean values (± standard deviation (SD)) of significantly differing textural features are presented in Table 1. These differences demonstrate textural alterations in radiographic HJS due to OA, which can be attributed to cartilage and subchondral bone tissue alterations associated to the disease. Articular cartilage performs mechanical functions providing transmission and distribution of high loads to underlying bone, maintenance of contact stresses at low levels, reduced frictional resistance to movement and shock absorption with these biomechanical properties being related to cartilage molecular–biochemical composition [35, 36]. Typical OA manifestations concern softening, ulceration, focal disintegration and the final loss of articular cartilage [37]. Alterations in chemical composition of articular cartilage have been associated with remodelling (increased density and stiffness) of subchondral bone in the form of subchondral sclerosis [38, 39]. Taking into account that structural alterations concern only osteoarthritic hips, differentiation of textural properties between normal and osteoarthritic HJS of unilateral OA-patients seems reasonable.

Previous studies on quantitative assessment of hip OA rely on measurements of the width or area of the radiographic HJS [11–15]. In the present study, hip OA-severity was estimated by the introduction of the HJS-narrowing index that evaluates the percentage of HJS-area difference between the osteoarthritic and the contralateral normal hip (Equation (1)). Repeated measurements of the HJS-area concerning the same observer were not found to differ significantly. Intraobserver reproducibility was found on average high for both the HJS area measurements (CV=3.4%) and the corresponding GLNU values (CV=3.9%). Similarly, interobserver reproducibility was also found high, 4.2% and 4.4% for HJS-area measurements and GLNU values, respectively. Mean values (±SD) of HJS-area for osteoarthritic and contralateral normal hips were found equal to 33.7 (±20.3) mm^2 and 105.0 (±23.8) mm^2, respectively. HJS-area values were statistically smaller ($p<0.001$) in osteoarthritic than in the contralateral normal hips, while previous studies on normal individuals have found no statistical differences between the two hips [13, 31]. HJS-narrowing index was evaluated for each one of the 18 unilateral patients and the mean and standard deviation of the HJS-narrowing index were calculated for the Mild/Moderate and Severe OA categories. Based on these means and standard deviations, classification rules (see Table 2) regarding the assessment of OA-severity were introduced (HJS-narrowing index Mean value ± 2SD). Referring to Table 2, an osteoarthritic hip was characterized as Severe if its HJS-narrowing index was greater than 77.9, as Mild/Moderate for index values within the interval [11.6, 77.9], and as Normal/Doubtful for OA if index values were lower than 11.6.

The introduced classification rules were tested against the KL classification of the unilateral OA patients (Table 3). Referring to Table 3, all hips corresponding to Mild/Moderate OA-severity category were classified correctly, while classification accuracy of hips with Severe OA was 77.8%, resulting in a relatively high overall classification precision of 88.9%. Taking into consideration that our method relies solely on the assessment of HJS-narrowing, deviations of our results from the KL scale may be attributed to the fact that the KL scale evaluates, besides HJS-narrowing, the presence of osteophytes, subchondral sclerosis, and subchondral cysts.

Feature selection on the basis of Pearson's correlation coefficients between each of the textural features extracted from osteoarthritic HJS-ROIs and the HJS-narrowing index are summarized in column 4 of Table 1. The strongest correlation was found between the HJS-narrowing index and the pathological GLNU textural feature ($r=-0.9$, $p<0.001$). This relationship is presented graphically in Figure 4. As it can be observed, a

Table 1. Mean values (±SD) of statistically significantly differing textural features of contralateral normal and osteoarthritic HJS-ROIs

Textural feature	Normal	Osteoarthritic	*R*
Grey level co-occurrence matrices-mean values			
Entropy	0.7 (±0.2)	0.8 (±0.2)	0.2
Contrast[a]	−0.7 (±0.2)	−0.6 (±0.2)	0.3
Inverse difference moment	0.9 (±0.1)	0.9 (±0.1)	−0.4
Sum of squares[a]	−0.3 (±0.3)	−0.2 (±0.3)	0.2
Difference entropy	0.2 (±0.1)	0.2 (±0.1)	0.3
Difference variance	0.2 (±0.1)	0.2 (±0.1)	0.3
Grey level run length matrices-mean values			
Short runs emphasis[a]	−0.5 (±0.1)	−0.4 (±0.1)	0.5
Long runs emphasis	12.9 (±3.0)	10.1 (±2.9)	−0.6
Grey level non-uniformity	415.2 (±92.8)	139.6 (±73.8)	−0.9
Run length non-uniformity	305.0 (±81.2)	110.0 (±59.8)	−0.7
Runs percentage[a]	−0.5 (±0.1)	−0.4 (±0.1)	0.6

SD, standard deviation; HJS-ROIs, hip joint space regions of interest.
[a]Values after logarithmic transformation ($\log_{10}$).

Table 2. Classification rules for assessment of osteoarthritis severity concerning HJS-narrowing index

Osteoarthritis severity according to KL grading scale	HJS-narrowing index, mean ±2SD	Classification rule
Severe	82.8 (±2·8.2)	HJS-narrowing index >77.9
Mild/Moderate	50.5 (±2·19.5)	11.6⩽HJS-narrowing Index⩽77.9

KL, Kellgren and Lawrence; SD, standard deviation; HJS, hip joint space.

Table 3. Comparison of results obtained by the KL scale and the proposed classification rules concerning HJS-narrowing index

Osteoarthritis severity according to KL scale	HJS-narrowing index>77.9 (Severe)	11.6 ⩽ HJS-narrowing index ⩽ 77.9 (Mild/Moderate)	Sum(s)	Success percentage
Severe	7	2	9	77.8%
Mild/Moderate	0	9	9	100%
Sum(s)	7	11	18	88.9%

KL, Kellgren and Lawrence; HJS, hip joint space.

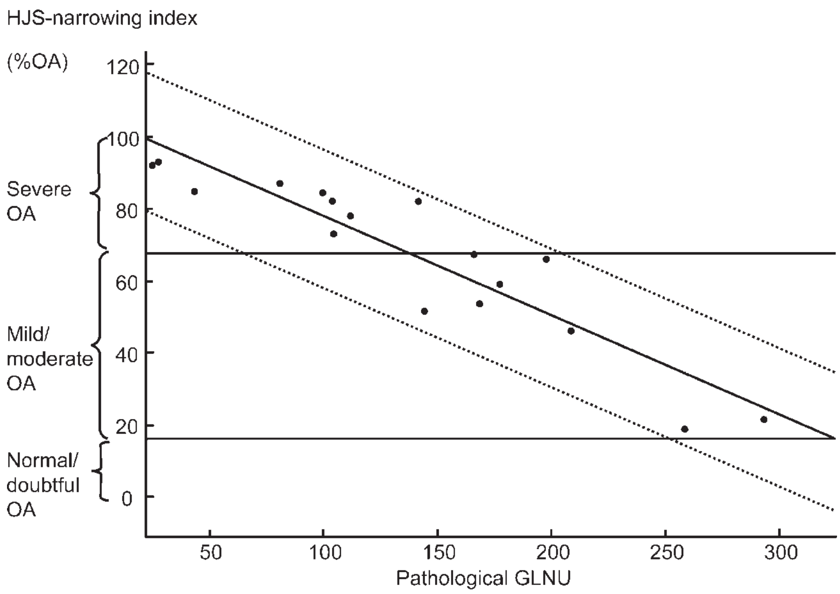


Figure 4. Hip joint space (HJS)-narrowing index versus pathological grey level non-uniformity (GLNU) textural feature. Solid line is the best line fitted to data points (•). Horizontal solid lines define the regions of osteoarthritis severity. Prediction bounds are denoted by dotted lines.

regression line, described by Equation (2):

$$\mathrm{HJS-narrowing} = -0.275 \times \mathrm{GLNU}_{\mathrm{path}} + 105 \qquad (2)$$

fitted data adequately. The negative slope of the regression line reflects the fact that in advanced stages of the disease, characterized by greater HJS-narrowing and thus higher HJS-narrowing index values, grey level intensities are more uniformly distributed (see Appendix 1) [30] within the region of radiographic HJS.

Subsequently, the selected GLNU textural feature was utilized in classification rules concerning the assessment of hip OA-severity. Based on the mean and standard deviation of the GLNU values, which were computed from the normal hips of the unilateral OA-group, a reference threshold value for GLNU, equal to 322.5 was employed (see Table 4) for characterizing a hip as either normal (GLNU>322.5) or osteoarthritic (GLNU ⩽ 322.5). Using the contralateral normal hip for establishing thresholds for hip osteoarthritis has been also employed in previous studies. Conrozier et al [13] suggested the establishment of reference values by measuring the HJS-width and HJS-area of the normal hips in patients with unilateral OA, while other studies used the minimum joint space width for classifying a hip as osteoarthritic [7, 40–44]. In the present study, however, a textural-feature based classification rule was employed instead.

Table 4. Classification rules for assessment of osteoarthritis severity concerning GLNU textural feature

Osteoarthritis severity according to KL grading scale	GLNU (Mean ± SD)	Classification rule
Severe	(88.0 ± 49.1)	GLNU<137.0
Mild/Moderate	(191.1 ± 56.4)	137.0 ⩽ GLNU ⩽ 322.5
Normal/Doubtful	(415.2 ± 92.8)	GLNU>322.5

KL, Kellgren and Lawrence; SD, standard deviation; GLNU, grey level non-uniformity

For verification purposes, GLNU values extracted from the HJS-ROIs of the unilateral osteoarthritic patients were subjected to the specific rule. It was found that 17/18 (94.4%) of the contralateral normal hips and a similar number (17/18) of the osteoarthritic hips were characterized correctly. When the same classification rule was applied to the bilateral OA-group, 24/28 (85.7%) hips were correctly characterized as osteoarthritic. In total, an overall classification accuracy of 90.6% (58/64), for assigning normal and osteoarthritic hips to the correct category, was achieved.

Besides characterizing a hip as normal or osteoarthitic, the capacity of GLNU textural feature was tested in establishing rules for differentiating hip OA-severity. Accordingly, rules for distinguishing hip OA-severity were formed, as shown in Table 4, that were defined on the basis of the mean and standard deviation GLNU values, obtained for hips assigned by the experienced orthopaedists to the same KL scale severity category. Referring to Table 4, a hip was characterized as Severe if its corresponding GLNU value was lower than 137.0, Mild/Moderate if its GLNU value was within the interval [137.0, 322.5], and as Normal/Doubtful for OA if its GLNU value was greater than 322.5. For verification

Table 5. Comparison of results obtained by the KL scale and the proposed classification rules concerning GLNU textural feature

Osteoarthritis severity according to KL scale	GLNU <137.0 (Severe)	137.0 ⩽GLNU⩽322.5 (Mild/Moderate)	GLNU>322.5 (Normal)	Sum(s)	Success percentage
Severe	7	2	0	9	77.8%
Mild/Moderate	1	8	0	9	88.9%
Normal/Doubtful	0	1	17	18	94.4%
Sum(s)	8	11	17	36	88.9%

KL, Kellgren and Lawrence; GLNU, grey level non-uniformity.

purposes, these classification rules were applied to the unilateral OA-group and results were compared with the KL scale classification (Table 5).

Referring to Table 5, the highest accuracy (94.4%) was achieved for normal hips. For hips with Severe OA the corresponding value was 77.8%, while for Mild/Moderate hips the accuracy was 88.9%. Finally, an overall classification accuracy of 88.9% (32/36) was achieved. To our knowledge, textural-feature based classification rules have not been proposed in previous hip OA studies.

Finally, the strong correlation of GLNU textural feature to the HJS-narrowing index was utilized to establish means of quantification of hip OA from textural properties of radiographic HJS (via $GLNU_{path}$ feature) employing Equations (1) and (2). This is important for monitoring the progression of the disease and for assessing the effectiveness of a treatment. Referring to the classification rules of Table 4, percentages corresponding to OA-severity categories could be established using Equation (2). Thus, index values for Severe OA were greater than 67.3%, for Mild/Moderate OA within the interval [16.3%, 67.3%] and for Normal/Doubtful OA less than 16.3%.

In this way, a hip may be assigned to an OA-severity scale and its osteoarthritis, if it exists, can be evaluated from its radiographic texture. This is of value because the OA of patients suffering from bilateral-OA, which is often the case, can be now quantified employing Equation (2), whereas OA quantification in a manner similar to Equation (1) applies only to patients with unilateral OA.

Conclusions

Alterations in the radiographic depiction of hip joint space texture, due to osteoarthritis, were evaluated and related to the severity of osteoarthritis, as defined by the KL scale. Specifically, the GLNU textural feature, which was selected considering its strong correlation to the HJS-narrowing index, demonstrated high classification accuracy in distinguishing hip OA-severity categories. In addition, considering the high reproducibility derived for the GLNU, the proposed method may have a contribution in monitoring of OA-progression, as well as in the evaluation of a chondroprotective therapy.

Acknowledgments

The authors thank the staff of the Departments of Orthopaedics and Radiology for their contribution to this work.

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Appendix 1

Description of the grey level non-uniformity (GLNU) textural feature defined by Galloway [30]

The grey-level run is a set of consecutive linearly adjacent pixels having the same grey level value. As length of the run is considered the number of pixels consisting the run. Each element $p(i, j)$ of a grey-level run length matrix represents the number of times an image contains a run of length j for grey level i, in a specific direction.

The mathematical definition of the GLNU textural feature is:

$$\mathrm{GLNU} = \frac{\sum_{i=1}^{N_g} \left(\sum_{j=1}^{N_r} p(i,j) \right)^2}{\sum_{i=1}^{N_g} \sum_{j=1}^{N_r} p(i,j)}$$

where: $p(i, j)$ is the (i, j)th element of grey level run length matrix, N_{g} is the number of grey levels in the image and N_{r} is the number of run lengths in the image.

Equally distributed runs throughout the grey levels, correspond to low values for GLNU and vice versa.