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Quantification of differences in bone texture from plain radiographs in knees with and without osteoarthritis

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S U M M A R Y

Objective: To quantify differences in bone texture between subjects with different stages of knee osteoarthritis (OA) and age- and gender-matched controls from plain radiographs using advanced image analysis methods.
Design: Altogether 203 knees were imaged using constant X-ray parameters and graded according to Kellgren–Lawrence (KL) grading scale (KL0: $n = 110$, KL1: $n = 28$, KL2: $n = 27$, KL3: $n = 31$, KL4: $n = 7$). Bone density-related and structure-related parameters were calculated from medial and lateral tibial subchondral bone plate and trabecular bone and from femur. Density-related parameters were derived from grayscale values and structure-related parameters from Laplacian- and local binary patterns (LBP)-based images.
Results: Reproducibilities of structure-related parameters were better than bone density-related parameters. Bone density-related parameters were significantly ($P < 0.05$) higher in KL2-4 groups than in control group (KL0) in medial tibial subchondral bone plate and trabecular bone. LBP-based structure parameters differed significantly between KL0 and KL2-4 groups in medial subchondral bone plate, between KL0 and KL1-4 groups in medial and lateral trabecular bone, and between KL0 and KL1-4/KL2-4 in medial and lateral femur. Laplacian-based parameters differed significantly between KL0 and KL2-4 groups in medial side regions-of-interest (ROIs).
Conclusions: Our results indicate that the changes in bone texture in knee OA can be quantitatively evaluated from plain radiographs using advanced image analysis. Based on the results, increased bone density can be directly estimated if the X-ray imaging conditions are constant between patients. However, structural analysis of bone was more reproducible than direct evaluation of grayscale values, and is therefore better suited for quantitative analysis when imaging conditions are variable.

Introduction

Osteoarthritis (OA) causes progressive degeneration of articular cartilage and abnormal changes in subchondral bone. Typical OA changes in the subchondral bone include thickening (sclerosis) as well as formation of osteophytes and subchondral bone cysts[1]. The actual definition of the extent of the subchondral bone varies, but it can be divided to the subchondral bone plate, located immediately beneath the calcified cartilage layer, and to the subchondral trabecular bone located beneath the subchondral bone plate[2–4].

Complete cure of OA does not currently exist, but the progression of the disease could be hindered if the diagnosis is confirmed

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at an early stage of the disease. Clinical diagnosis of OA is routinely based on clinical examination and changes on plain radiographs. Radiography is cheap, fast, and widely-available imaging modality. Articular cartilage is not visible on plain radiographs but OA changes including joint space narrowing, subchondral bone sclerosis and cysts, and osteophytes, can still be diagnosed[5]. Kellgren–Lawrence (KL) grading scale[6] is typically used for grading of OA from plain radiographs. However, KL grading is subjective, semi-quantitative, and according to the literature its intra- and inter-rater reliability varies from only moderate to substantial[7–9]. The diagnostic value of simple plain radiography could be enhanced if new quantitative and user-independent image analysis algorithms are developed and applied.

In earlier studies, quantitative evaluation of knee radiographs in OA have typically concentrated on the measurement of joint space width (JSW)[10,11]. Some studies have calculated an estimate for bone density from plain radiographs[12,13]. However, image acquisition parameters and post-processing algorithms significantly affect the density estimates[13]. In addition to JSW and density estimation, texture analysis is a potential method to extract quantitative and user-independent information of bony structures from plain radiographs. Texture analysis of bone is not as dependent on the imaging conditions as direct evaluation of grayscale values. In recent texture analysis studies, progression of OA has been evaluated from standard digital knee radiography using signature dissimilarity measure (SDM) method[14] and fractal signature analysis (FSA)[15]. Previously, fractal-based algorithms have been also applied for macro-radiographs[16–20] and standard film radiographs[20–23] from OA knees. The potential of gradient- or Laplacian-based image processing algorithms that have already shown their effectiveness in hip fracture studies[24,25], have not been studied in OA radiographs yet.

Another potential technique for the texture analysis of bone is local binary patterns (LBP) method that has been widely used in machine vision field[26]. It is simple and quite insensitive to monotonic grayscale variations, e.g., in X-ray images to changes in radiation intensity (quantity of charge, so called mAs value). One dimensional LBP method has recently been applied in the trabecular bone analysis from the calcaneus[27]. However, LBP analysis from knee involving calculation of the texture parameters from LBP-based image might reveal more important information on bone structure.

The aim of the current study is to quantify differences in bone density and structure between subjects with different stages of knee OA and controls from plain radiographs using advanced image analysis methods. We hypothesize that simple grayscale parameters estimating subchondral bone density and quantitative bone structure-related texture parameters derived from Laplacian- and LBP-based images would be different among OA patients than among age- and gender-matched controls.

Methods

Study subjects

This study consisted of male patients ($n = 53$, mean age (standard deviation (SD)): 59.4 (5.2) years, body mass index (BMI): 30.5 (4.7) kg/m^2) with unilateral or bilateral knee OA and healthy age-matched male controls ($n = 50$, age: 59.5 (4.4) years, BMI: 27.8 (3.2) kg/m^2). From the original study population ($n = 107$)[28,29], four patients were excluded due to missing or different resolution of radiograph. Exclusion criteria included previous hip or knee fracture, surgery of lower extremities (arthroscopy was allowed), clinical or radiological hip OA, a knee or hip joint infection, congenital or developmental disease of lower limbs, paralysis of lower extremities, and rheumatoid arthritis or spondyloarthritis. The detailed exclusion criteria has been published earlier[28,29]. The Ethics Committee of the Kuopio University Hospital approved the study design.

Acquisition of plain radiographs and grading of the knees

Anterior-posterior weight bearing radiographs from both knees were obtained using computed radiography (full extension, constant X-ray parameters: tube voltage = 60 kV, quantity of charge = 25 mAs, focus-skin distance = 110 cm) and digitized with a pixel resolution of 0.2 mm × 0.2 mm. The knees were classified according to the KL grading scale[6], in which 0 is normal and 4 is severe OA. KL grades were not known during the quantitative image analyses. In three knees, lateral side was more affected than the medial side and these knees were excluded from the analyses (one knee had KL grade 3 and two knees KL grade 4) to homogenize the study sample.

Both knees of the subjects (total number of samples = 203) were analyzed using custom-made MATLAB software (v.7.9.0; MathWorks Inc., Natick, MA, USA). First, the radiographs were converted to 8-bit grayscale images (pixel intensity value range: 0–255) and pixel size in the image was calibrated using a calibration ball with a diameter of 30 mm included in each radiograph. Medial and lateral JSWs and minimum JSWs (mJSW) were measured manually from the middle part of the condyles and from the narrowest point of the joint (Fig. 1), respectively.

Selection of regions-of-interest (ROIs)

Altogether six rectangle-shaped ROIs were extracted from the tibia and femur and one elliptical-shaped ROI (variable size) from

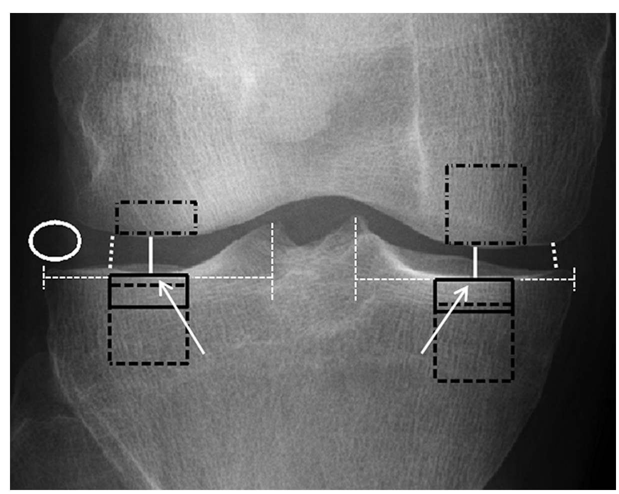

Fig. 1. A schematic figure describing manual placement of ROIs. Subchondral bone plate ROIs were placed immediately under the cartilage–bone interface in the middle part of medial and lateral condyles of tibia (ROIs shown with black-colored rectangles with continuous line). The center points (white arrows) were checked visually and they were about a half of the horizontal distance between the outer border of tibia and a vertical line drawn from the medial or lateral tibial spine (white dashed lines). Subchondral trabecular bone ROIs (black squares with dashed line) were placed immediately below the subchondral bone plate of tibia and were aligned horizontally with the subchondral bone plate ROIs. When placing femur ROIs (black rectangles with dash-dotted line), horizontal alignment of subchondral bone plate ROIs, plateau in the middle part of femoral condyles, and patella were considered. JSWs, shown with white continuous line, and minimum JSWs (white dotted line) were measured manually from the middle part of the condyles and from the narrowest point of the joint, respectively. Soft tissue ROI (white ellipse) was placed in the lateral side of the joint. For more details, see the Methods section.