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Automatic assessment of the knee alignment angle on full-limb radiographs☆

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ABSTRACT

In this study a fully automatic assessment of the knee alignment angles in full-limb radiographs was developed and compared to manual standard of reference measurements in a prospective manner.

The data consisted of 28 knees which were gathered from total-leg radiographs of 15 patients (12 males and 3 females with a mean age of 29.4 ± 6.9 years) consecutively.

For statistical evaluation, a leave-one-out cross-validation was performed. The pattern recognition and consequently the fully automatic assessment were successful in all patients.

The automatically measured angles highly correlated with the standard of reference ($r = 0.989$). The mean absolute difference was 0.578° (95% CI: 0.399–0.757°). 82% of the angles differed less than 1° from the standard of reference, 46% differed less than 0.5° and 31% differed less than 0.2°. The automatic method showed a high agreement between repeated measurements (+0.515° to −0.429°).

The automatic assessment of alignment angles in full-limb radiographs were equal to the manual assessment. No measurement related user interaction was necessary to achieve results.

1. Introduction

Anterior–posterior long-leg radiographs are part of a standardized protocol to evaluate axial alignment of the lower limb [1,2]. The assessment of lower limb alignment is important in orthopaedic surgery, particularly when planning surgery such as total knee arthroplasty or high tibial wedge osteotomy [3–5].

The knee alignment is of importance in the planning of corrective knee surgery, and the degree of postoperative angulation is known to be directly associated with outcome [6,7]. In addition, the degree of mal-alignment correlates with the progression of cartilage loss assessed by magnetic resonance tomography [8] and the joint space narrowing measured on radiography, and is therefore of prognostic value in knee osteoarthritis (OA) [9]. The varus knee alignment induces degenerative changes in the medial knee compartment whereas the valgus knee alignment affects the lateral knee compartment. Considering this, and the fact that lower limb alignment can be thought of as a predictor for osteoarthritis, its importance is highlighted. Moreover, the information concerning the alignment of the lower extremity is also significant in the postoperative follow-up.

Until recently, quantification of the knee alignment imposed difficulties due to insufficient reproducibility because of poorly defined landmarks and imprecise measurement techniques [10]. Limited possibilities of patient positioning during set-up, with common factors such as flexion and rotational alterations, frequently influences the apparent alignment on the lower limb radiograph [11], especially in severe cases pre-operatively and after

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surgery. In addition, the image may be distorted by inclined X-ray beams [12,13]. In the digital era, assessment of radiographs which are down-scaled in size to fit on review monitors cause loss of precision.

Aside from the acquisition inaccuracies mentioned above, observer variability is a further important factor possibly reducing the accuracy of manual measurements of limb alignment and mainly depends on experience, skill and attitude of the reader. In the past, intra- and inter-reader measurement reliability has been moderate. Even when using the most advanced radiographic positioning protocols, mechanical axis measurements reliability has not proved to be superior to standard clinical readings [10,14]. Hence, while minor deviations in the mechanical axis can have a considerable impact on the progression of OA, they are usually not detected in standard knee alignment assessment as they are below the limit of detection [10]. For this reason the precise and accurate quantification of the knee alignment angle is highly relevant in clinical practice, but hampered by observer-variability. The purpose of this study was therefore to prospectively test a fully automatic assessment of knee alignment angles in full-limb radiographs by validating its accuracy and precision.

2. Patients and methods

The software applied in this study was developed by one of the authors (P.W.) within this research project and was provided free of charge. There was no conflict of interest for this author throughout the study. The protocol of this pilot study was approved by the local ethics committee.

2.1. Patients

Patients referred from the orthopedic outpatient clinic, scheduled for total knee arthroplasty, total hip arthroplasty or osteotomy procedures were consecutively included.

Patients were excluded if they formerly have had surgery on their hip, knee or ankle.

The study included 15 patients, 12 male and 3 female, with a mean age 29.4 + 6.9 years. A total of 28 knees were evaluated, 2 knees had to be excluded as the poor image quality did not allow manual or automatic evaluation, and since not indicated clinically, the radiographs were not repeated.

2.2. Data acqusition

All examinations included full-limb radiographs for routineclinical purposes. There was no radiation administered for mere study purposes. In addition, data safety and patient anonymity was guaranteed by pseudonymisation of image data.

Each patient underwent long-leg radiography of the lower limb using a digital radiography system. The alignment angles ranged from -8.53° (varus) to $+9.43^\circ$ (valgus), with a mean angle of $-0.7 + 3.9^\circ$.

Radiographs were performed in a standardized anterior–posterior and standing position without footwear and the extremities positioned so that the patellae were facing forward. The gonads were shielded. ADC (AGFA Diagnostic Centre) full body cassette holder with three overlapping ADCC/MD (AGFA Diagnostic Centre Cassette, medium) phosphor storage plates (35 cm × 43 cm) were used for digital radiographs (AGFA-GEVAERT, Belgium). The software used was MIMOSA VIPS.1.3.00 with an AGOS.A.0.8.08 system. According to individual patient constitution, a setting of 77–96 kV and of 40–100 mA s was applied.

2.3. Definition of the knee alignment angle

The knee alignment angle is defined as the mechanical axis formed by a line from the centre of the femoral head through the centre of the knee to the centre of the ankle joint [15,16]. The centre of the femoral head was defined as the circum-centre of a triangle formed by three points along the medial part of the femoral head, dividing it into portions of roughly equal size. The centre of the knee was defined to be in the middle between the intercondylar notch and the centre of the tibial spines. The centre of the ankle joint was defined as the centre of the ankle mortise.

2.4. Training of the algorithm

The segmentation method was based on active shape models (ASMs) and incorporates statistical models of shape and local appearance [17,18]. These models were built from a set of 14 instances of the right femoral bone, 13 instances of the right tibial bone and 15 instances of both left femoral bone and left tibial bone. For this study the training instances were gathered from full-limb radiographs of 15 patients, 12 male and 3 female. Since evaluation was performed in a leave-one-out procedure, and 15 left and 13 right knee joints were included in this study, training was performed on 14 left and 12 right knees joints at a time, while the automatic segmentation was performed on the remaining case.

To collect samples for the ASM training algorithm, the contours of the bones were captured manually by a musculoskeletal radiologist (P.P., 8 years of experience), aided by a computer application, which deploys an algorithm called “Live-Wire” [19]. This method allows a semi-automatic and interactive segmentation of the bones on full-limb radiographs.

2.5. Automatic assessment of alignment angles

After the algorithm had been trained, the pre-processing, image analysis and assessment of the knee alignment angles were performed fully automatically with a standard PC. The measured angle is returned in degrees, with positive values denoting a valgus orientation and negative values representing varus alignment. Optionally, the application can view each image augmented by a plot of the detected mechanical axes.

The algorithm involves the following steps:

1. The position, size and orientation of the femora and tibiae are estimated automatically, and serve as initialisation reference of the segmentation algorithm for each respective bone (Fig. 1).
2. The bone contours are segmented by active shape models [20], which fit a statistical bone model to the image.
3. A fine adjustment of the segmentation and landmark positioning is performed based on the image information on each landmark. This is handled by maximizing the quality of fit of each landmark with respect to local image content without resulting in an implausible shape.
4. Based on the landmarks of the segmented bones, a final ASM-search is performed to refine each joint region definition. The segmented bones and joint regions as well as the resulting mechanical axes are shown in Fig. 2.
5. Angles are measured between the landmarks defined based on the fitted bone models.

2.6. Standard of reference

For statistical evaluation, we performed a “leave-one-out cross validation” on the set of 28 knees available from the patients included in this study.