COMPUTER METHODS AND PROGRAMS IN BIOMEDICINE 124 (2016) 138–147

journal homepage: www.intl.elsevierhealth.com/journals/cmpb

Modeling skeletal bone development with hidden Markov models

Daniela Giordano, Isaak Kavasidis, Concetto Spampinato*

The Department of Electrical, Electronics and Computer Engineering, University of Catania, 95125 Catania, Italy

ARTICLE INFO

Article history:
Received 2 July 2015
Received in revised form
6 October 2015
Accepted 15 October 2015

Keywords:
Medical imaging
Image processing
Machine learning

ABSTRACT

This paper presents a tool for automatic assessment of skeletal bone age according to a modified version of the Tanner and Whitehouse (TW2) clinical method. The tool is able to provide an accurate bone age assessment in the range 0–6 years by processing epiphysial/metaphysial ROIs with image-processing techniques, and assigning TW2 stage to each ROI by means of hidden Markov models.

The system was evaluated on a set of 360 X-rays (180 for males and 180 for females) achieving a high success rate in bone age evaluation (mean error rate of 0.41 ± 0.33 years comparable to human error) as well as outperforming other effective methods. The paper also describes the graphical user interface of the tool, which is also released, thus to support and speed up clinicians' practices when dealing with bone age assessment.

1. Introduction

The advancements in computer science have always boosted a large number of scientific fields by both facilitating and hastening the execution of repetitive and/or complex tasks. Image processing methods, in particular, have been used in a variety of applications in diagnostic medicine since their mere conception [1,2] improving the diagnostic accuracy [3,4]. Projection radiography was the first non-invasive method to depict the internal structures of the human body and it is currently one of the most used imaging methods. During the last decades a notable increase of interest in determining accurately the bone age by processing X-Rays, has been observed. This interest arises from the fact that having an accurate and objective assessment of the age of an individual may result extremely useful in many applications ranging from detecting and evaluating hereditary, hormonal or developmental disorders [5,6] to creating indisputable evidence in legal cases where the real age of a person can determine his eligibility for criminal sanctions [7], legal rights [8], etc.

In the clinical practices, two approaches have been used for skeletal bone age assessment: the Greulich and Pyle (GP) [9] and the Tanner and Whitehouse (TW) [10] methods. Both approaches have been tested from the scientific community and their validity is already confirmed [11–14].

The GP method, which is the simplest and most intuitive one, relies on comparing a subject's X-Ray of the left wrist to a gold standard atlas categorized according to age and sex. The TW2 method uses a-priori knowledge and creates a detailed analysis of the features of twenty predetermined regions of interest (ROIs) located in the left hand's bones, including epiphysis/metaphysis ROI (EMROI), carpal ROI (CROI), radius, and ulna. Each ROI is evaluated by assigning to it a letter, which represents the developmental status, ranging from A, meaning that the bone is completely absent, to I, which represents

* *Corresponding author*. Tel.: +39 0957387902.
E-mail addresses: dgiordan@dieei.unict.it (D. Giordano), kavasidis@dieei.unict.it (I. Kavasidis), cspampin@dieei.unict.it (C. Spampinato).

http://dx.doi.org/10.1016/j.cmpb.2015.10.012
0169-2607/

a fully developed, mature bone. As a final step, by summing up all the ROI scores the effective bone age is calculated.

The GP method is less complicated and generally faster than the TW2 method and as a consequence the most used in the clinical practices. However, TW2 offers better reproducibility and accuracy [15] and, because of its modular nature, is proner to automation [16].

Although much research has been carried out, the problem of estimating accurately the bone age of an individual is far from being solved [17–19].

In this paper we present a method and a tool aiming at determining skeletal bone age based on X-Rays of the left wrist according to a modified version of the TW2 method based on EMROIs only, combined with hidden Markov model-based classifiers for accurate bone development modeling. In the next section a review of the existing approaches is found, while Section 3 describes the proposed method and the GUI based on it. Section 4 reports the performance analysis on a dataset of 360 X-Rays and in the last section, conclusions and future work are given.

2. Related works

Early attempts for "automating" the process of skeletal bone age assessment can be dated back to the early 90s, and in particular, in [20] where the authors present the first system employing image processing techniques, namely Sobel Gradient and thresholding, to make the image more suitable for the bone age assessment task. Measurements of the phalanxes were compared to the standard phalangeal length table [21] and accordingly the bone age was calculated. While this method suffered from the classical "infancy" problems (e.g. image quality, reproducibility etc..), it can be considered as one of the first steps towards more complex and accurate systems for bone age assessment. Since then, many other methods for assessing skeletal bone age, especially based on the TW2 method, have proposed and they can be categorized in three main groups: fuzzy-based, deformable models-based and machine learning-based.

Fuzzy logic has been widely exploited for bones classification. In [22] the authors present an automatic skeletal bone age assessment system for young children (from 0 to 7 years old) using only carpal bones. This method initially employs fully automatic carpal bone segmentation and morphological feature analysis and, subsequently, applies a fuzzy classification approach to bone development. Other fuzzy-based methods combined with morphological features of the carpal bones can be found in [23] where the authors also integrate Principal Component Analysis and statistical correlation or Support Vector Machines [24] to build a growth model of the carpal bones, stating a success rate of 87–89%, although they considered a relatively large admissible error of 1.5 years. Fuzzy classifiers are used in [25] for automating the GP method. Although it achieves a very high accuracy rate at lower age groups (0–2 years), its performance deteriorates when X-Rays of older subjects were used.

Deformable models (and especially Active Shape Models) have been largely used for skeletal bone age assessment [26–28]. Despite deformable model based approaches are capable of modeling EMROI shapes, they are ad-hoc solutions relying on many parameters, and, thus their results depend largely on the quality of input images. The authors in [29] suggest that one of the main difficulties in evaluating bone age, is the irregular (i.e. largely varying) development of the trapezium and trapezoid bones and they propose a method, based on the integration of anatomical knowledge and trigonometry theory for the TW2 assessment.

Machine learning techniques have been also used, e.g., in [30], an X-Ray image is first segmented using a K-means clustering algorithm on the gray-level co-occurrence matrix, although the authors do not report detailed performance evaluation. A Support Vector Machine and correlation prototypes [31], and in [32], Support Vector Regression and smart class mapping have been proposed that, however, perform poorly in terms of accuracy. Contrary to the majority of the existing systems based on a single evaluation method, BoneXpert [33] is an automatic skeletal bone age assessment system combining both TW and GP methods. The main drawback of BoneXpert, however, is its high image rejection rate, meaning that it does not process low quality images and it often requires a heavy preprocessing step in order to make the image appropriate for processing.

While there exist many computer-based EMROI classification systems that employ machine learning approaches (e.g. Neural Networks, Fuzzy Classifiers, Support Vector Machines, etc.) one of the main limitations is the lack of methods to model bone shapes effectively and dynamically. To deal with this issue we employ Hidden Markov Models, which is a model of a sequential process changing states at discrete sequence intervals thus able to model ROIs' discrete stage. A further contribution of this paper is the integration of several existing works, from preprocessing to finger extraction to stage assignment, into a unified tool which can be used by clinicians.

3. The proposed tool

Generally, the existing applications for skeletal bone age evaluation follow a standard workflow (Fig. 1) model: the input image is initially processed by noise removal (for enhancing image clearness); afterwards, background removal methods are employed to highlight only the parts necessary for the further classification.

Before presenting our method, a brief description of the TW2 clinical method is given.

3.1. *The Tanner–Whitehouse method*

The TW2 method is based on a predefined standard of bone maturity depending on age. It employs 20 ROIs located on the first, third and fifth finger and the carpus of the left hand. The finger ROIs are called EMROIs (Epiphyses/Metaphyses ROI) and the carpal ones (including radius and ulna) CROIs (Fig. 2). The maturity of the bone is determined by the state of the epiphysis: if it is completely absent, it is an initial developmental state, otherwise, if it is completely fused to the metaphysis, bone maturation is completed. The development progression of each ROI can be divided into discrete stages, with each one assigned a letter from A (epiphysis is absent) to I