Biomedical Signal Processing and Control 18 (2015) 303–316

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

journal homepage: www.elsevier.com/locate/bspc

Surface-based rigid registration using a global optimization algorithm for assessment of MRI knee cartilage thickness changes

Changyong Guo [a], Yuanzhi Cheng [a,*], Haoyan Guo [a], Jinke Wang [a], Yadong Wang [a], Shinichi Tamura [b]

[a] *School of Computer Science and Technology, Harbin Institute of Technology, Harbin 150001, China*
[b] *Center for Advanced Medical Engineering and Informatics, Osaka University, Suita 565-0871, Japan*

ARTICLE INFO

Article history:
Received 6 April 2014
Received in revised form 6 February 2015
Accepted 9 February 2015
Available online 6 March 2015

Keywords:
Cartilage segmentation
Changes over time
Femoral cartilage
Global optimization
Registration

ABSTRACT

Registration methods have become an important tool in many medical applications. Existing methods require a good initial estimation (transformation) in order to find a global solution, i.e., if the initial estimation is far from the actual solution, incorrect solution or mismatching is very likely. In contrast, this paper presents a novel approach for globally solving the three dimensional (3D) rigid registration problem. The registration is grounded on a mathematical theory—Lipschitz optimization. It achieves a guaranteed global optimality with a rough initial estimation (e.g., even a random guess). Moreover, Munkres assignment algorithm is used to find the point correspondences. It applies the distance matrix to find an optimal correspondence. Our method is evaluated and demonstrated on MR images from porcine knees and human knees. Compared with state-of-the-art methods, the proposed technique is more robust, more accurate to perform point to point comparisons of knee cartilage thickness values for follow-up studies on the same subject.

1. Introduction

Osteoarthritis (OA) of the knee is chronic disease associated with deterioration of the joint cartilage. As OA progresses, the cartilage gets thinner and in severe cases breaks down losing its entire functionality. Changes in the morphology of knee cartilage (such as the cartilage thickness) can be well detected with magnetic resonance imaging (MRI) [1].

Thickness changes over the short time scale useful in drug development (6–12 months) are likely to be in the sub-millimeter region [2]. A number of approaches [3–5] have shown that small changes in thickness between two different time points can be determined by registering the two sets of different time points and computing change at each point of the bone–cartilage interface or bone surface. A point-based rigid registration algorithm using the bone–cartilage interface as a reference for tracking time-dependent thickness changes of local knee cartilage can be found in Ref. [3]. A rigid registration approach using bone surface points for evaluating focal volume changes of knee cartilage in clinical study is presented in Ref. [4]. There is also a rigid registration approach for quantifying local (focal) hip cartilage thickness changes in longitudinal study, see Ref. [5]. These algorithms require a good initial transformation in order to converge to the globally optimal solution, otherwise only a local optimum is attained.

In this paper, we describe a novel framework for obtaining the globally solution. The algorithms in this paper are based on the Lipschitz optimization and then using a hyper-cuboid-and-hyper-ball (HCnHB) algorithm. We introduce a “Lipschitzation” to the cost function. After making the cost function globally Lipschitzian, a global search over the transformation space can be carried out effectively. The advantage of our approach is that it always gives the correct solution with a random initialization; it is noticeable, however, that if a good initialization is available then our approach runs much faster, as the good initialization can provide a near search bound. A coarse registration based on the principal axes transformation is therefore used for identifying reducing the search bound. Moreover, by exploiting the special hexagram-64-tree data structure of the 3D registration problem itself and of the six-dimensional Euclidean motion (rotation and translation) space, we propose a hyper-cuboid-and-hyper-ball (HCnHB) algorithm to implement the global search. To our knowledge, no such efficient global method is yet available for the registration of knee bone surfaces on serial MR images obtained at different times.

---

[*] Corresponding author. Tel.: +86 451 86413309.
E-mail address: yzcheng@hitwh.edu.cn (Y. Cheng).

http://dx.doi.org/10.1016/j.bspc.2015.02.007
1746-8094/

2. Materials and methods

2.1. Data preparation and MRI acquisition

Our study was divided into two stages. In the first stage, the 30 fresh frozen pig knees and 30 knees of patients (11 men, 19 women; age range, 32–67 years; mean age, 52.6 years) were used for evaluating the registration accuracy. Each porcine knee was scanned twice; and 30 knees of patients were imaged twice at baseline (BL) and 12 months (M12). The status of the joints range from healthy to osteoarthritic according to the Kellgren–Lawrence index (KL_i) [6], a radiographic score established by X-rays between 0 and 4 where $KL_i = 0$ is healthy, $KL_i = 1$ is doubtful OA, $KL_i = 2$ is minimal OA, $KL_i = 3$ is moderate OA, and $KL_i = 4$ is severe OA. Based on the confirmation of radiologist and 2 orthopedists, 30 patient knees at baseline have grade of $KL_i \leq 2$. In the follow-up study visit (at 12 months), 19 knees have grade of $KL_i = 2$, and 11 knees have grade of $KL_i = 3$.

In the second stage, we performed the thickness comparison of the same subject at different time points. In the animal experimentation, registration was performed for undeformed femoral cartilages in 5 fresh pig knees and those obtained in a 5-h static compression experiment with a loading force of 100 kg [7,8]. We displayed the cartilage thickness changes after the 3D registration of cartilage–bone interface before and after 5 h of static compression. In the clinical experiment, 30 above-mentioned patient knees were examined for showing that our study was well suited for the follow-up clinical application of OA knees.

The protocol MRI was a fat-saturated 3D spoiled gradient recalled echo in sagittal plane with TR = 9.0 ms, TE = 4.2 ms, flip angle = 30°, FOV = 320 × 320 mm, slice thickness 2 mm, and matrix 256 × 256, scan time 4:30. Images were obtained on a General Electric 1.5-T MRI scanner (GE Medical Systems, Milwaukee, WI) with a standard transmit receive extremity coil. An isotropic voxel size of $1.0 \times 1.0 \times 1.0\,\text{mm}^3$ can be created by the interpolation method. 3D isotropic interpolation is an exhaustive computation. To reduce the computational time, therefore, the slice thickness was reduced from 2 to 1 mm using the zero-filling interpolation.

2.2. Segmentation and cartilage thickness

2.2.1. Cartilage segmentation

Cartilage is segmented from MR images using a semi-automatic segmentation technique by Lynch et al. [9]. The technique consists of the following three steps.

(1) *Manual initialization*: (i) the extremities of the cartilage sheet within each slice (two points per slice with femoral cartilage visible) (Fig. 1a), and (ii) six points within the articular cartilage from the central slice of the scan, and also from example slices within both the medial and lateral compartment of the knee.

(2) *Detection of the cartilage sheet*: The computer then optimizes the positions of these points and extrapolates them to neighboring slices (Fig. 1b), automatically adjusting the points so that they are within the cartilage sheet within each slice (Fig. 1c and d). The computer has then provided its best estimate of the 3D extent of the cartilage sheet covering the femoral condyles (Fig. 1e). The observer can then correct any incorrectly placed points (usually occurring at the extreme medical and lateral extents of the joint, and occasionally at the boundary between the trochlear groove and the femoral condyles).

(3) *Detection of the bone–cartilage interface and the cartilage–synovium interface*: The computer then automatically adjusts this cartilage sheet into the bone–cartilage interface (inner-boundary) and the cartilage–synovium interface (out-boundary) of the cartilage (Fig. 1f), with a final review and correction by the observer. This technique can be performed in a batch mode, with many scans being initialized at once, with a later review of the detection of the cartilage sheet being performed. The cartilage can be automatically segmented in a later analysis, followed by a review and correction of the results.

2.2.2. Bone surface reconstruction

The 3D bone shape is reconstructed from MR images using a multi-step process. First, the bone surface is segmented using the aforementioned method with manual boundary initialization and manual correction for accurate segmentation (see Fig. 2). The 2D segmented contours are then processed to form a 3D surface representation (3D reconstruction) of the bone surface based on a network of triangles, by connecting the points of one 2D contour with its closest counterparts on the consecutive 2D contour.

By resampling bone surface, resolution of the triangulated bone surface, i.e., the number of vertices of triangles in the network can be selected interactively by the user. In the present study, registrations were performed at a resolution of approximately 4760 vertices for one porcine knee and approximately 6900 vertices for one patient knee on the triangulated bone surfaces. This serves to reduce the computational complexity, particularly by saving time in operating the following registration algorithm, which should preferably work in real time. The networks of two data sets constitute the input to the registration algorithm.

2.2.3. Cartilage thickness

The bone–cartilage interface and articular surface are required for the computation of 3D cartilage thickness measurements using either 3D minimum Euclidean distance or a normal vector by searching outwards from the bone surface. Searching outwards along the normal appeared to offer increased reliability around local anomalies such as osteophytes, which often present in our images from patients with OA. Unfortunately, in certain geometrical situations this method can fail locally. Therefore, for each point on the bone–cartilage interface, the 3D minimum Euclidean distance point on the articular surface is found and the corresponding minimum Euclidean distance is assigned as its thickness value. So each point in the bone surface corresponding to the bone–cartilage interface has a thickness value assigned to it.

To quantify local cartilage thickness changes over time, corresponding point must be identified on the follow-up image. After identifying the corresponding point, error of our algorithm is within 1 mm (see Table 6). Thus, the identified corresponding point may not be on the bone–cartilage surface of follow-up image. In such situation, closest point on the bone–cartilage surface is found and cartilage thickness is estimated from this point. In addition, a trilinear interpolation is performed for the closest point at a non-integral location.

2.3. Surface-based registration

Surface-based registration involves the determination of the surfaces of the images to be matched and the minimization of a distance measure between these corresponding surfaces. The surfaces are generally represented as set of large number of points obtained by segmenting contours in contiguous image slices. There may be a requirement for the points to be triangulated. After performing the bone surface generation based on a network of triangles, each femoral bone surface is composed of the vertices of the network of triangles. The main aim of the present study is to find a truly globally optimal transformation and triangle vertices correspondences (i.e., triangles correspondences).