ARTICLE IN PRESS
JID: KNOSYS [m5G;January 25, 2017;10:33]

Knowledge-Based Systems 000 (2017) 1–10

Contents lists available at ScienceDirect

Knowledge-Based Systems

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

Small bowel motility assessment based on fully convolutional networks and long short-term memory

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ARTICLE INFO

Article history:
Received 2 November 2016
Revised 13 December 2016
Accepted 18 January 2017
Available online xxx

Keywords:
Small bowel motility
Cine-MRI
Deep neural networks
Fully convolutional networks
LSTM

ABSTRACT

Assessment of small bowel's motility plays an important role in the diagnosis of small bowel disease. Conventional assessment methods rely on hand-designed features or manual guide-line drawing, which results in difficult modeling and high time consumption, thus they are still inefficient and impractical for clinical uses. With the help of deep neural networks, we introduced a semi-automated approach, replacing hand-designed features with automatic feature extraction, and an automated approach, eliminating manual guide-line drawing, to assess small bowel motility by automatically marking cross-sectional diameters on small bowel images, measuring temporal fluctuation of diameter lengths, and evaluating contraction frequency. Experiment results show that proposed methods could estimate small bowel contraction frequency correctly. The difference between predicted diameter lengths and one manually labeled is within reasonable range, and estimated frequency is close to the groundtruth. Therefore, proposed methods can be utilized for diagnosis of small bowel disease, which will assist radiologist in decision-making.

1. Introduction

1.1. Small bowel motility assessment

As the major organ for digestion and desorption, small bowel shows various and complex motility patterns. Small bowel disorder is the reason of many clinical symptoms, like Crohn's disease, irritable bowel syndrome, intestinal pseudo-obstruction, and bacterial overgrowth [1,2]. Therefore, quantitative analysis of small bowel motility patterns is important for diagnosis of small bowel disease.

1.1.1. Observation of small bowel motility

The performance of small bowel motility assessment depends on the way of observation. There are different kinds of radiologic modality for the examination of small bowels, such as ultrasonography (US), cross-sectional tomographic (CT), and wireless capsule endoscopy. As a non-invasive modality [1,3], Magnetic Resonance Imaging (MRI) allows us observing both intra-luminal and extra-luminal abnormalities [4–6]. Moreover, Cine-MRI (cinema-MRI) enables observation of small bowel's temporal motion, therefore, in this research, the assessment is made on small bowel images captured from cine-MRI.

1.1.2. Evaluation of small bowel motility

Based on the segmental motion we observed, small bowel disorder can be detected using quantitative analysis. Conventional quantitative analysis is usually performed by transit time assay, manometry, inpedancometry, and tensiometry. These approaches, however, are available in only limited institutions, and the reproducibility and specificity of these methods are comparatively low [5]. Some of these methods are invasive or potentially harmful to patients, because of ionizing radiation. Therefore, a non-invasive and safe way to assess small bowel motility is needed.

Since small bowel motility shows different contraction patterns between healthy people and patients with gastrointestinal disorders, such as chronic intestinal pseudo-obstruction and irritable bowel syndrome [5], the assessment in this research is conducted by measuring contraction frequency. By measuring small bowel's contraction frequency from cine-MRI sequence, the assessment is performed safely, with no harm to patients.

In order to measure small bowel's contraction frequency, which characterized small bowel's segmental motion, we need to first measure the temporal changes of small bowel's diameter. Therefore, assessing small bowel motility in this research is made by measuring small bowel's diameter in a temporal sequence. The assessment in this research is conducted by first automatically marking diameters from cine-MRI frames containing a bowel loop, then measuring the diameter's length in each frame, and finally

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http://dx.doi.org/10.1016/j.knosys.2017.01.023
0950-7051/

calculating contraction frequency based on diameter lengths in a temporal sequence.

In the rest of this paper, the marked diameter, represented as a mask image, is called the diameter pattern in this paper. Diameter length is measured by the distance between two endpoints in the diameter pattern. These diameters of the same bowel loop form a temporal diameter sequence, called the segmental motion pattern.

1.2. Deep neural networks

Convolutional Neural Networks (CNNs) are quite powerful in learning nonlinear features hierarchically, especially spatial features of images [7,9–12]. The core idea behind this is local receptive fields, which is inspired by mammalian visual cortex [13]. This characteristic makes CNNs able to learn hierarchical features and propagate them through the network. As traditional CNNs are very popular in high-level vision tasks, they are not quite fit pixel-wised learning tasks, such as pose estimation and semantic segmentation, since their local invariance structure is more suitable for learning abstraction of spatial details rather than precise localization [14]. Besides, conventional CNNs have difficulties in learning holistically, for their in-network local image transformations.

As a variant of CNNs, Fully Convolutional Networks (FCNs) [15] have been successful in dense prediction tasks such as semantic segmentation [15,16], edge detection [17], and skeleton extraction [18]. FCNs replace fully connected layers of traditional CNNs with convolutional layers. They have built-in up-sampling layers to make the output as the same size as the input, achieving end-to-end learning. Concerning that the segmental motion learning in this research needs to be precise for accurate analysis, also, the global information is necessary when learning small bowel's diameter pattern, we investigated using FCNs to predict the location and orientation of small bowel's diameter.

FCNs are not good at learning temporal features, which is significant in estimating small bowel's segmental motion. Therefore, Long Short-Term Memory (LSTM), as a popular Recurrent Neural Networks (RNN) architecture specialized in sequence learning, is introduced to learn temporal features of small bowel's image sequences. It has built-in memory gate to retain long-term information [19]. Byeon et al. [20] shows that LSTM network is overall suited for image processing tasks, moreover, authors in [21–26] investigated its effectiveness of sequence to sequence learning. Given this context, it is suitable for LSTM to learn small bowel's segmental motion pattern from input sequences.

1.3. Proposed methods

With the help of cine-MRI, there have been much effort being devoted to the quantitative analysis of small bowel motility [1,4,7,8]. These approaches, however, often rely on elaborate feature designing and manual guide-line drawing before quantitative analysis, which makes the assessment difficult and inefficient.

1.3.1. Semi-automated approach

In this research, we introduced a semi-automated approach, based on FCNs, to learn the non-linear mapping from the image containing small bowel loops to the image of cross-sectional diameter, without elaborate feature designing. This procedure is semi-automated because it needs a guide-line as prior information, telling the location and orientation of the diameter, thus it is called FCN-Baseline in this paper.

1.3.2. Automated approach

The semi-automated approach needs manual guide-line drawing, which is inconvenient for clinical uses. Therefore, we propose an automated approach using FCN stacked with LSTM, called FCN-LSTM. In this approach, a FCN model learns the guide-line, rather than manually depicting, to accelerate the whole process, and a LSTM model learns the mapping from a sequence of small bowel images to a sequence of corresponding diameters.

1.3.3. ROI selection

It should be noted that, both FCN-Baseline and FCN-LSTM require manual-selected ROI as input. As the most complex motion area in human body, small bowel shows complex contraction conditions, especially in 2-D images. There is overlapping between bowel loops and displacement of bowel wall. Therefore, ROI still needs to be selected by experienced radiologist.

In FCN-Baseline, the ROI, which contains a small bowel loop we are going to analysis, is selected in every input frame, while in FCN-LSTM, it only needs manual ROI selection once for the whole sequence, only the first frame of the input sequence is sent to experienced radiologists for determining ROI. In both approaches, the whole cine-MRI sequence will be cropped according to the ROI after ROI selection.

1.3.4. Diameter length measurement

In addition, Principle Components Analysis (PCA), as a dimension reduction method, is introduced in both approaches for transforming the predicted 2-D diameter pattern into a 1-D line representation, then the diameter length is obtained by measuring the length of this line.

In general, proposed methods assess small bowel motility by automatically marking cross-sectional diameters on small bowel images, measuring temporal fluctuation of diameter lengths, and evaluating contraction frequency, to help diagnosis of small bowel disease. Proposed semi-automated approach replaces elaborate feature designing with automatic feature extraction, and the automated approach we proposed removes manual guide-line drawing. An overview of small bowel motility assessment in this research is displayed in Fig. 1.

2. Related works

There are some researches focusing on analyzing small bowel's contraction property to assess small bowel motility; some of them used cine-MRI as the imaging technique to capture small bowel's temporal movement. Authors in [1,3,7] investigated the potential of MRI as a non-invasive method for monitoring small bowel motility.

Early studies like Patak et al. [3] measured small bowel's diameter manually, which is time-consuming and labor-intensive. Researches such as Wakamiya et al. [1] and Froehlich et al. [7] started using a guide-line to help measuring cross-sectional diameters. Diameters in these methods, however, were still delineated manually.

Some researches used techniques, like joint nonrigid registration [4], or level set with automatic initialization [8], to delineate luminal diameters automatically. These approaches, however, rely on elaborate manual feature designing, which is difficult to be applied to other tasks.

In addition, approaches like [1,7,8] rely on manual guide-line drawing before measuring small bowel's diameter, which makes the procedure inefficient due to manual interfere.

Table 1 shows the comparison between these approaches briefly.

Deep neural networks, which have the ability of automatic feature extraction, have been introduced to medical image segmentation in recent studies. Dhungel et al. [27] proposed a method using CNNs based on structured prediction model to segment breast masses in mammograms. Roth et al. [28] presented an automated approach for pancreas segmentation with the help of CNNs. Moreover, Havaei et al. [29] investigated segmenting brain tumor