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A detection-driven and sparsity-constrained deformable model for fascia lata labeling and thigh inter-muscular adipose quantification

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ABSTRACT

Quantification of the thigh inter-muscular adipose tissue (IMAT) plays a critical role in various medical data analysis tasks, e.g., the analysis of physical performance or the diagnosis of knee osteoarthritis. Several techniques have been proposed to perform automated thigh tissues quantification. However, none of them has provided an effective method to track fascia lata, which is an important anatomic trail to distinguish between subcutaneous adipose tissue (SAT) and IMAT in the thigh. As a result, the estimates of IMAT may not be accurate due to the unclear appearance cues, complicated anatomic, or pathological characteristics of the fascia lata. Thus, prior tissue information, e.g., intensity, orientation and scale, becomes critical to infer the fascia lata location from magnetic resonance (MR) images. In this paper, we propose a novel detection-driven and sparsity-constrained deformable model to obtain accurate fascia lata labeling. The model's deformation is driven by the detected control points on fascia lata through a discriminative detector in a narrow-band fashion. By using a sparsity-constrained optimization, the deformation is solved from errors and outliers suppression. The proposed approach has been evaluated on a set of 3D MR thigh volumes. In a comparison with the state-of-the-art framework, our approach produces superior performance.

1. Introduction

The inter-muscular adipose tissue (IMAT) is an essential tissue component of the thigh. It lies within the fascia lata surrounding the leg musculature. The fascia lata, shown in Fig. 1, is a fibrous membrane giving off sheaths to the thigh muscles. Different from the subcutaneous adipose tissue (SAT), IMAT encompasses and permeates skeletal muscle blocks, with which it shares a direct vascular connection (Durheim et al., 2008) as illustrated by a T1-weighted magnetic resonance (MR) image in Fig. 2.

IMAT has been considered as an important predictor of the human body's metabolism, muscle function, and mobility function (Addison et al., 2014). The volume of IMAT seemed to be inversely associated with physical activity and the increase of IMAT volume could contribute to losses in muscle strength (Manini et al., 2007). Tuttle et al. showed that IMAT impacts physical performance (Tuttle et al., 2012). Quantification of IMAT can also provide an important cue for the diagnosis of knee osteoarthritis (OA). Knee OA is a type of disease of degenerative joints, including articular cartilage and subchondral bone, which is the most prevalent arthritis in older people. Maly et al. revealed the relationship between IMAT volume and knee extensor strength, and physical performance among women with or at risk of knee OA using magnetic resonance imaging (MRI) (Maly et al., 2011, 2013). In addition, a further study in Dannhauer et al. (2014) has shown that the increase of IMAT content is associated with structural and pathological progression of knee OA in women. Therefore, an accurate quantitative assessment of thigh IMAT is crucial in many medical and clinical analyses, such as leg functional quality analysis, metabolic dysfunction or knee OA diagnosis from a large number of MR images.

In recent years, several techniques have been proposed to perform automated muscle/tissue segmentation and IMAT assessment. A 2D segmentation by gradient vector flow (GVF) based active contour was used to assess IMAT and other tissues in thigh (Positano et al., 2009). Makrogiannis et al. (2012) incorporated a parametric

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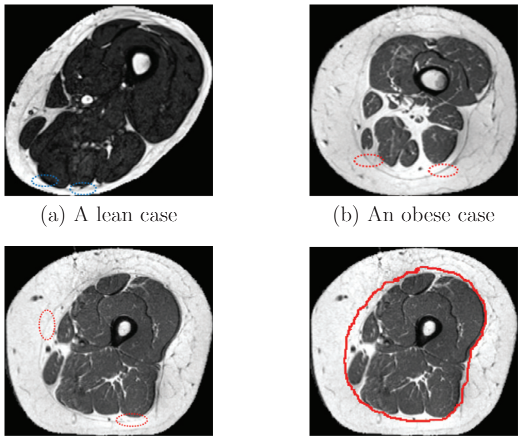

(a) A lean case (b) An obese case (c) Weak fascia lata boundary (d) Ground truth of fascia lata

Fig. 1. (a) In a lean case, the fascia lata (blue marked regions) is close to muscle regions. (b) The red marked regions show that the fascia lata is away from muscle boundary in an obese case. (c) Weak fascia lata boundary is in the red marked regions. (d) The red-labeled boundary shows a ground truth by expert. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

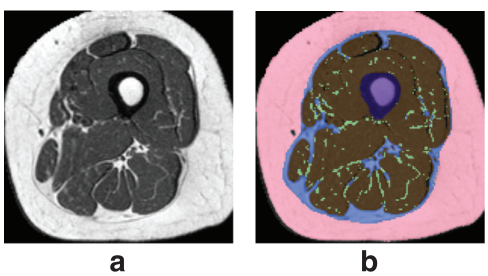

Fig. 2. (a) A cross-sectional and T1-weighted MR image of thigh. (b) Different tissue labels: muscle (brown), SAT (pink), IMAT (blue), intra-MAT (green), bone and marrow (purple). Bone and marrow have low and high pixel intensities in MR image, respectively. Adipose tissues (AT) have high pixel intensity. SAT, also called superficial fascia, is the adipose layer between the dermis and the deep fascia around the thigh muscles. Muscles have intermediate intensity. IMAT and intra-muscular adipose tissues (intra-MAT) are defined as the AT's visible between muscle groups and muscle fibers, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

deformable model and unsupervised tissue clustering for IMAT extraction. Valentinitsch et al. (2013) used a model based on k-means clustering and mathematical morphology to classify and delineate IMAT and SAT. In Andrews et al. (2011) and Baudin et al.(2012) the authors incorporated shape/appearance priors into their segmentation methods to segment individual skeletal muscle blocks. In our previous study (Tan et al., 2014), we proposed a robust framework to handle the parameter sensitivities in segmentation and high variation in thigh data by utilizing a variational Bayesian Gaussian mixture model and the metamorphs (Huang et al., 2004).

So far, all the above-mentioned existing methods assume that the contour of the general muscular region is the boundary separating SAT and IMAT if we call the enclosed area including all the skeletal muscle blocks as the general muscular region. Since the fascia lata is close to the muscle groups in normal subjects, such an assumption is acceptable. However, this assumption does not hold for pathological subjects, because the fascia lata may not be close to muscle regions (as shown in Fig. 1(b)). When processing the image data from subjects with pathological changes, such as obesity or muscle looseness, the existing methods may not have accurate fascia lata delineation due to the following challenges. First, the fascia lata has a low-contrast contour. Part of its appearance is weak or even missing (Fig. 1(c)), and nearby tissues may have similar image texture as the fascia lata. Such ambiguous image cues may mislead traditional segmentation methods like deformable model and edge detection. Second, the shape of fascia lata has a large variation. Its morphology and structure may change due to the affecting disorders and diseases of the thigh. Third, there exist unknown noises and imaging artifacts in medical images, which can impact the accuracy of image analysis. For example, the bias field is a low-frequency noise which can cause intensity and contrast inhomogeneities in MR images. Lastly, robust and precise segmentation for objective and consistent measurements is challenging in clinical trials due to the significant geometric and physiologic variations in subjects as well as the diverse sources the medical images were acquired from.

In this paper, we propose to label the fascia lata through its reconstruction by a sparsity-constrained deformable model driven by learning-based detection. Specifically, the approach includes the following three parts. (a) The initialization of the deformable model is implemented by an efficient unsupervised tissue segmentation integrating global image context and shape refinement. The initialized surface is modeled as a set of meshless vertices, which provides a regularization (prior term) to preserve the local shape during model evolution. (b) The model evolution is driven by a force (data term) which is derived from the detected control points on fascia lata. The control points are detected in a narrow-band fashion from the initialized surface using features like local image context and global orientation. (c) To overcome errors and outliers in the detection, a sparsity constraint (Zhang et al., 2012a) has been utilized to optimize the model deformation. The deformation result can be forwarded back to step (a) for iterative updates until the model converges. The proposed method (I) captures both global and local image information for the model initialization and control points detection; (II) integrates geometric information and sparse outliers expression into the model optimization. As a result, this method is able to handle ambiguous boundaries like the one shown in Fig. 1(c). The evaluation on a set of 3D T1-weighted MR thigh volumes shows that our method produces superior performance compared to state-of-the-art approaches. The proposed method can produce robust IMAT quantification in clinical analyses.

The rest of the paper is organized as follows. Section 2 reviews relevant work about thigh muscle extractions using atlas-based segmentations, the popular deformable models, and shape priors and sparsity constraint methods. Section 3 presents the proposed framework and its implementation for the fascia lata labeling. Section 4 shows the experimental results on a dataset from OA clinical trials and discussions. Finally, we conclude in Section 5.

2. Related work

Atlas-based automated approaches have been used to effectively segment objects of interest in biomedical images. An atlas is a pair of a target scan and a corresponding manual labeling image. The atlas-based segmentation is estimated using image registration, and hence a single segmented result is propagated (Ashburner and Friston, 2005; Iosifescu et al., 1997). Numerous atlas-based variations have been proposed. Slagmolen et al. (2007), Okada et al. (2007) and Yan et al. (2014) demonstrated that the atlas-based methods can provide a reliable initial segmentation for refinement. Aljabar et al. (2009) introduced an atlas selection to accelerate the label fusion and obtain more accurate segmentation. Recently, the multi-atlas approach with joint label fusion (Wang et al., 2013) and its optimization with a generative probability model (Wu et al., 2014) achieved very good accuracies in brain parcellation challenges. Some authors have utilized atlas-based methods for thigh muscle extraction (Ahmad et al., 2014; Prescott et al., 2011). However, the performance of

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