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Automatic measurement of pennation angle and fascicle length of gastrocnemius muscles using real-time ultrasound imaging

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ABSTRACT

Muscle imaging is a promising field of research to understand the biological and bioelectrical characteristics of muscles through the observation of muscle architectural change. Sonomyography (SMG) is a technique which can quantify the real-time architectural change of muscles under different contractions and motions with ultrasound imaging. The pennation angle and fascicle length are two crucial SMG parameters to understand the contraction mechanics at muscle level, but they have to be manually detected on ultrasound images frame by frame. In this study, we proposed an automatic method to quantitatively identify pennation angle and fascicle length of gastrocnemius (GM) muscle based on multi-resolution analysis and line feature extraction, which could overcome the limitations of tedious and time-consuming manual measurement. The method started with convolving Gabor wavelet specially designed for enhancing the line-like structure detection in GM ultrasound image. The resulting image was then used to detect the fascicles and aponeuroses for calculating the pennation angle and fascicle length with the consideration of their distribution in ultrasound image. The performance of this method was tested on computer simulated images and experimental images in vivo obtained from normal subjects. Tests on synthetic images showed that the method could identify the fascicle orientation with an average error less than 0.1°. The result of in vivo experiment showed a good agreement between the results obtained by the automatic and the manual measurements ($r = 0.94 \pm 0.03$; $p < 0.001$, and $r = 0.95 \pm 0.02$, $p < 0.001$). Furthermore, a significant correlation between the ankle angle and pennation angle ($r = 0.89 \pm 0.05$; $p < 0.001$) and fascicle length ($r = -0.90 \pm 0.04$; $p < 0.001$) was found for the ankle plantar flexion. This study demonstrated that the proposed method was able to automatically measure the pennation angle and fascicle length of GM ultrasound images, which made it feasible to investigate muscle-level mechanics more comprehensively in vivo.

1. Introduction

Muscle activation, in response to signals from the central nervous system, is essential to force generation and motion regulations, which is composed of a sophisticated sequence of events that occurs at individual muscle fiber level or at the entire muscle level [1]. Muscle imaging is a field of research with great promise to investigate muscle activation because the biological and bioelectrical characteristics of muscles are closely related to their structure. It has been well manifested that the geometric layout of the fascicles within the skeletal muscle is highly related to muscle contractions through muscle imaging [2–8], which is primarily represented by its muscle architecture parameters (MAPs): fascicle length, pennation angle, muscle thickness and cross-sectional area. These morphometric parameters of skeletal muscle are therefore of great interest to understanding of the skeletal muscle activation, especially from a biomechanical perspective. Recently, sonomyography (SMG) was proposed to non-invasively measure the muscle activities by quantitatively recording the real-time change of MAPs obtained using ultrasound imaging [9]. Many similar studies have been reported recently. Ultrasound is a proper non-invasive real-time imaging modality for muscle structure imaging [10,11]. Ultrasound has been used for examining the static change in MAPs in response to contraction [5–8], ageing [12–15], physical training [16–19] and fatigue [20,21], and has also been used to evaluate how muscle fibers operate during motion [22–26]. The SMG and similar approaches are gradually becoming a reliable research and clinical tool and show potentials in both diagnosis and

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rehabilitation assessment in vivo with the ability to detect muscle activity at different depths and locations.

Among the reported MAPs that can be identified in ultrasound images, the pennation angle and fascicle length are the most often used parameters to quantify changes in fascicle geometry of gastrocnemius (GM) during completion of dynamic tasks because the ability of GM to generate force is mainly determined by its fascicle length and fascicle-shortening velocity. It has been figured out that the fascicles of GM remain around the plateau region of their force–length relationship with the benefits of the relatively larger force generation under different walking speeds [23]. On the other hand, previous research has also pointed out that key differences exist in GM fascicle-shortening velocity with both speed and gait [23–26]. The fascicle-shortening velocity corresponding to the muscle force generation at the peak time was reported to increase with walking speed, which made force–length relationship shift out from the plateau (optimal) region and diminished the ability of the muscle to generate high peak forces [26]. By contrast, fascicle shortening corresponding to the muscle force generation at the peak time was shifted to much slower velocities when switching from walking to running at the same speed, resulting in a large increase in peak muscle force and an increase in GM power output [26]. The modulation of interaction between the GM fascicle and tendon tissue also took place in response for the effective utilization of the tendon elasticity in mechanical demands during human motion [25,26]. Thereby, it is promising to investigate muscle-level mechanics of GM more comprehensively in vivo by assessing fascicle geometry change with SMG.

Many previous researches involved manual assessment of SMG, including fascicle length and pennation angle, in a sequence of ultrasound images for dynamic muscle functional assessment. However, manual assessment in ultrasound images is time-consuming, tedious, and subjective, making it difficult for implementation in muscle function analysis of dynamic task. Some automated approaches with image processing techniques were therefore developed to estimate the fascicle length and pennation angle in ultrasound images. There are mainly two kinds of approaches. The first one is based on feature tracking between ultrasound images with optical flow or cross-correlation [27–31]. The second one is based on feature detection in single ultrasound image [32–36].

Using the feature tracking method, small regions of interest were manually identified in the first frame, and tracked with Lucas–Kanade algorithm [29] or cross-correlation [27] from one frame to the next. Feature tracking in ultrasound images is challenging because it must cope with muscle deformation and speckle noise. The features in small regions of interest may undergo significant changes in appearance or intensity, and even lost in the images. These approaches failed to track fascicle continuously, and only derive the contractile length change of whole muscle. Cronin et al. [28] treated manually selected fascicle region as a whole patch to estimate affine flow parameters with Lucas–Kanade optical flow algorithm under the assumption that the object being tracked (the muscle) conforms to the homogenous affine transformations. Based on the assumption of straight fascicles, the fascicle endpoints were manually defined within the region, and then the fascicle shape was estimated with the endpoints and the global optical flow parameters. Darby et al. [30] proposed Bayesian multiple hypothesis approach with particle filter and the Lucas–Kanade optical flow algorithm to recover the changing fascicle shape and estimate the fascicle curvature. However, the fascicle characteristics estimated with these two approaches are only a representation of the mean values within the fascicle region of interest. Furthermore, the speckle, a granular pattern in ultrasound image due to the de-phased echoes from the scatters, is a multiplicative factor reflecting an interaction between ultrasound and media scatterers, and varies over time due to the dynamic scatterers in biology tissues [37,38]. The assumption that the intensity of image is constant in optical flow calculation therefore cannot always be guaranteed between two consecutive ultrasound images. This might also affect the performance of feature tracking approaches, especially for the relatively large muscle movements.

The feature detection method is based on the observation in muscle ultrasound images that the aponeuroses are distributed as continuous hyper echoic bands and the fascicles are usually non-uniformly distributed as line-like structures [4,39]. The aponeuroses and fascicles can then be identified through locating these line-like structures in images under the assumption of the straight fascicles [32–35]. The Hough transform was firstly used to detect the line-like structure in muscular-skeletal images with a revoting strategy (RVHT) [32]. Hough transform could realize better localization since it depended on the edge map of the image. But, it is sensitive to speckle noise ascribed to poor performance of conventional edge detector in ultrasound image. Zhao and Zhang [35] proposed localized Radon transform (LRT) to perform Radon transform to detect the fascicles in ultrasound images with the revoting strategy in regions where fascicles were supposed to be found. This approach achieved better performance through avoiding the usage of edge detector. However, its localization ability was not as good as Hough transform since the interested line-like structures are distributed as hyper echoic bands in ultrasound images. It is a tradeoff to achieve accurate localization with good performance. Moreover, the appearance of speckle patterns often obscures and masks diagnostically important features in ultrasound images, which also increases the difficulty of accurate measurement of fascicle in the images. Furthermore, the standard Hough transform and Radon transform tend to detect diagonal lines rather than vertical or horizontal lines since they are anisotropic (directional).

In this study, we proposed an automatic method to extract the fascicle length and pennation angle from the ultrasound images of GM using multiple resolution analysis and Hough transform under the assumption of the straight fascicles and the observation of repeated fascicles in GM muscle [11]. This method increased the weights of line-like structures in Hough transform using Gabor wavelet [40,41], so as to achieve better localization and alleviate the influence of speckle noise. The methods were described in the following section. This new method was tested with both simulated images and real ultrasound image sequences of GM muscle during plantar flexion, and the corresponding results were presented in Section 3. Discussions were given in Section 4 and conclusion was finally drawn in Section 5.

2. Methods

The automatic method for measurement of pennation angle and fascicle length is summarized in the flowchart in Fig. 1. A bank of Gabor wavelet was designed to enhance the detection of aponeuroses and fascicles in the region of interest (ROI) confirmed in musculoskeletal ultrasound image sequence. The ROI was defined to contain superficial and deep aponeuroses and the GM muscle region, as shown in Fig. 2. The magnitude components of decomposition of ROI with Gabor wavelet at different scales and orientations were combined and used as the weight in the line detection stage, as described in the following subsections. The position and orientation of the aponeuroses were first recognized using the normalized Radon transform with the consideration of the distribution of aponeuroses in ultrasound images. The fascicle orientation was then determined as the predominant orientation in ROI by using the maximum variance in the Hough transform because the parallel fascicles at unequal distances relative to each