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Continuous fascicle orientation measurement of medial gastrocnemius muscle in ultrasonography using frequency domain Radon transform

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ABSTRACT

Fascicle orientation is one of the most widely used parameters for quantifying muscle function in mechanical analysis, clinical diagnosis, and rehabilitation assessment. Ultrasonography has frequently been used as a reliable way to measure the changes in fascicle orientation of human muscles non-invasively. Conventionally, most such measurements are conducted by a manual analysis of ultrasound images. This manual approach is time consuming, subjective and not suitable for measuring dynamic changes. In this study, we developed an automated tracking method based on a frequency domain Radon transform. The goal of the study was to evaluate the performance of the proposed method by comparing it with the manual approach and by determining its repeatability. A real-time B-mode ultrasound scanner was used to examine the medial gastrocnemius muscle during contraction. The coefficient of multiple correlation (CMC) was used to quantify the level of agreement between the two methods and the repeatability of the proposed method. The two methods were also compared by linear regression and a Bland–Altman analysis. The findings indicated that the results obtained using the proposed method were in good agreement with those obtained using the manual approach ($\text{CMC} = 0.94 \pm 0.03$, $\text{difference} = -0.23 \pm 0.68^\circ$) and were highly repeatable ($\text{CMC} = 0.91 \pm 0.04$). In conclusion, the new method presented here may provide an accurate, highly repeatable, and efficient approach for estimating fascicle orientation during muscle contraction.

1. Introduction

Ultrasound imaging is a frequently used approach for in vivo assessment of skeletal muscles. It has been introduced to quantify morphological changes in human muscle [1,2] such as fascicle length [3–5], fascicle orientation [6–9], muscle thickness [10,11], and cross-sectional area [12–14]. Since these morphological parameters are significantly related to the mechanical properties of human muscle, they are increasingly used to quantify muscle function in both research and clinical diagnosis [15–18].

Pennation angle, defined as the angle between the fascicle orientation and deep aponeurosis orientation, is one of the most widely used parameters for quantifying muscle function. Measurements of fascicle pennation are often used in physiological and biomechanical modeling studies to estimate the force-generating capacity of muscles [19]. The degree of muscle pennation is related to both the amount of contractile tissue packed along the tendons and the fiber length and is indicative of the force-generating capacity and shortening velocity of the muscle as well as being connected with the elastic properties of the muscle-tendon complex [20]. Although the definition of pennation angle depends on orientations of both the fascicle and the deep aponeurosis, the orientation of the fascicle plays a more important role than the orientation of the deep aponeurosis in muscle contraction; some evidence even exists that indicates that the fascicle angles can be substitutable for pennation angles in some muscles [21]. Moreover, the automatic detection of fascicle orientation is more difficult than that of deep aponeurosis. Therefore, methods that detect fascicle orientation have drawn most of the attention of researchers.

Traditionally, manual assessment of ultrasound images has been used to obtain morphological parameters [21,22]. However, this procedure is time consuming and subjective. Recently, some

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automatic/semiautomatic approaches have been developed for tracking fascicle features such as length, orientation, and curvature [4–9,23–26]. For the tracking of fascicle orientation, most of the methods are based on the detection of linear features of the fascicles [6–9]. Zhou et al. utilized a Hough transform to project the edge map of an ultrasound image into Hough space [6]. Then, the local peaks were searched for in the Hough space by a revoting procedure to extract the straights lines in the image space one by one. This method relies greatly on the performance of the edge detector, which could be compromised by speckle noise. Moreover, the revoting strategy requires some prior information, such as the line width so that a detected line can be removed and the threshold for determining when the revoting procedure should stop. To overcome the shortcomings of the Hough transform, some studies used the Radon transform, which does not require edge detection and its inherent integration feature is less susceptible to background noise [8,9], in place of the Hough transform. Zhao et al. used a localized Radon transform and the revoting strategy to sequentially extract the individual linear features [9]. Instead of using the peaks of corresponding lines, Rana et al. adopted the variability of the Radon transform to find the dominant fascicle orientation [8]. Compared to the line detection based method in [9], this method can produce a more representative result, an average fascicle orientation within the fascicle region. Although the methods based on a Radon transform can improve the robustness of linear feature detection, they still have some inherent drawbacks. First, an ultrasound image usually contains fascicles with multiple segments or even fascicles with curvature. These features have comparably lower peaks or less variability in the transform space while compared with straight fascicles and may, thus, reduce the performance of Radon transform based methods. Second, the adopted integration map can be influenced by the length of the integration path; hence, these methods may be sensitive to the size or location of the manually digitized region of interest (ROI).

Most of the studies mentioned above assumed that the fascicles under investigation were straight lines. However, some studies have indicated that fascicles may in fact curve [27–29]. Therefore, a few automated approaches were developed to track nonlinear fascicle shape changes from ultrasound images [23–25]. Cronin et al. proposed a method based on the Lucas–Kanade algorithm to track the movement of the fascicle endpoints (proximal and distal) [5]. Although the reported work only considered length of a straight fascicle, it may be possible to account for curvature if fascicles are defined using more than two landmarkers. Darby et al. developed another method of automatically segmenting images into fascicle and aponeurosis regions and tracking movement of features, independently in localized portions, by a Kanade–Lucas–Tomasi feature tracker [23]. Their work was further extended in another study, in which fascicle curvature was tracked and quantified in vivo during a range of movements [24].

In this study, we proposed a novel approach in which we used a Radon transform in the frequency domain to track fascicle orientation. The key idea is that a Fourier transform is first applied to the ultrasound image and then a Radon transform is used in the frequency domain to find a dominant orientation of the fascicles. This new algorithm was evaluated using a set of clinical musculoskeletal ultrasound images.

2. Methods

2.1. Experiment

Six healthy male participants (age: 23 ± 2 years (mean ± SD); weight: 68.3 ± 5.2 kg; height: 170.2 ± 10.1 cm) with no history of neurological, cognitive, metabolic, cardiovascular, pulmonary, or lower limb musculoskeletal impairment volunteered to participate in this study. Human subject ethical approval was obtained from the Medical Ethics Committee of the Medical School of Shenzhen University and informed consent was obtained from each subject prior to the experiment. Each subject was directed to sit on a chair with his/her hip at an angle of 90° and a knee angle of 120°. During measurement, the subject was instructed to perform a voluntary ankle flexion for 10 s during which the ankle flexion angle was varied between a maximized dorsiflexion and a maximized plantar flexion within the limits of the subject. A custom-designed multi-degree adjustable bracket was used to fix the ultrasound probe, and the ultrasound images of the medial gastrocnemius muscle were recorded using an ultrasound image scanner (DC-6, Mindray, China) with a standard 7L4, 7.5 MHz linear probe. The video output was digitized by a video A/D converter and saved to a computer disk.

2.2. Image sequence processing

In this study, a novel image processing method using a frequency domain Radon transform was developed in MATLAB (The MathWorks, Natick, MA, USA) environment to track continuous fascicle orientation changes in ultrasound image sequences. The method we used is automatic except for manually digitizing the ROI on the first frame. The tracking process consists of three steps:

1. ROI digitization: We manually digitized the fascicle ROI between the superficial and deep aponeuroses on the first frame of the ultrasound sequence by implementing a graphics user interface to provide an intuitive and simple way to manually segment the ROI into a rectangle shape. The major goals of this step were to maximize the area of the ROI in order to obtain more textural information about the fascicles and to ensure that the ROI does not overlap with the superficial and deep fascias to avoid introducing different frequency components. A good example of an ROI digitization is shown in Fig. 1.
2. Orientation estimation: We used a Fourier transform to transform the ROI image to the frequency domain and then transformed the frequency domain data using a Radon transform. The peak point was located in the Radon space. Its corresponding angle was then accepted as the dominant fascicle orientation in the original ROI image.
3. Tracking method: After obtaining the fascicle orientation from the first frame, we used a tracking method to find the continuous

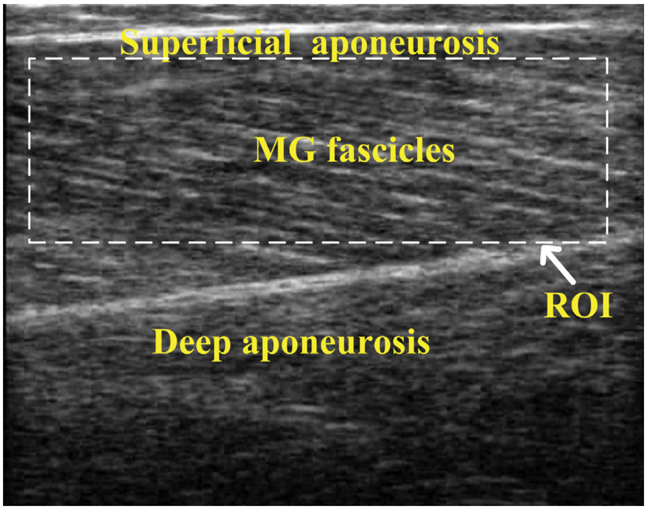

Fig. 1. ROI digitization.