ORIGINAL ARTICLE

A Proactive Technique for Pennation Angle Estimation of Skeletal Muscles Using Ultrasound Imaging

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Received: 24 April 2023 / Accepted: 19 April 2024

Abstract

Purpose: The concrete construction of the musculoskeletal modeling is efficiently performed using information obtained from patients rather than collected from cadavers. In this study, we have endeavored to propose an automated technique that calculates the skeletal muscle pennation angle of patient ultrasound images and compares it with manual evaluations of the same images.

Materials and Methods: The proposed technique consists of three steps after the process of collecting the data from 30 volunteers of different muscles of the upper and lower limb. The first step is to improve the contrast in the image and identify the important details in the image through the use of two methods that depend on a fuzzy inference system, and this step is considered essential to prepare the image in the next step. The Hough Transform was used to follow the muscle fibers and draw them as lines, this is the second step. The third step is to calculate the angle and compare it with the manual evaluation that was done depending on the ultrasound machine options.

Results: The results reveal that there is a slightly difference between manual and automated evaluations of pennation angle for biceps (upper limb muscle) and gastrocnemius (lower limb muscle) as 8.6% and 0.45% respectively. Furthermore, the manual assignment of pennation angles is significantly slower, taking minutes, while the automated approach takes only a few seconds. Automated measurements take 85% more time compared to manual measurements.

Conclusion: There is no significant difference between measurements based on t-test. In future work, we aspire to a wider application of this technique to other muscles in the body and to activate it as an option available in the ultrasound device.

Keywords: Pennation Angle; Skeletal Muscle; Ultrasound Imaging; Fuzzy Inference System and Hough Transform; Biomedical Image Applications.

DOI:

1. Introduction

The tissue of the skeletal muscles has a flexible ability of increasing tension. This assists in the maintaining of the straight body position, moving limbs and absorbing shock. Basically, skeletal muscle consists of a set of muscle fibers. The geometric arrangement of muscle fibers (oblique or straight) has an impact on the muscle strength and its ability to move. Muscle fibers are connected with each other to form pennation angle, this is the angle of insertion of muscle fibers into the aponeurosis [1-5].

The evaluation of the pennation angle helps in the assessment of the muscle strength based on different muscle statuses. For example, muscle relaxation and muscle tension, where the value of pennation angles are different for each case, see Figure 1 [6].

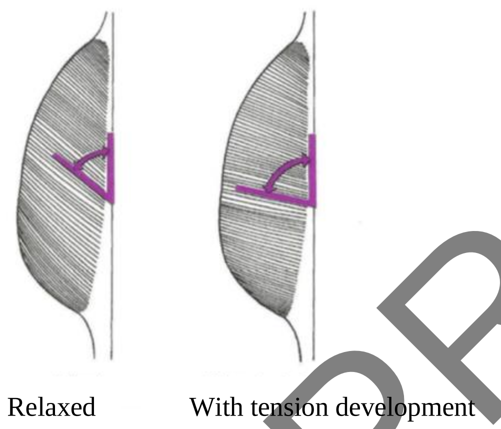


Figure 1. Represents pennation angle of the skeletal muscle and its change in terms of muscle relaxation and tension [6]

The brachialis muscle is a muscle located in the upper arm, underneath the biceps brachii muscle. It plays a significant role in elbow flexion, assisting in the bending of the forearm at the elbow joint [7]. Manual measuring the pennation angle of the brachialis muscle can provide valuable information about its architecture and function. Changes in the pennation angle may occur in response to factors such as muscle hypertrophy, training adaptations, or pathological conditions. However, the manual method is inherently prone to over or underestimation of the measurement and it requires a significant amount of time [8]. Several studies have been published and are concerned with the determination of the muscle pennation angle. One of these studies was introduced by Zhou *et al.* (2015) [9] and was carried out on the gastrocnemius muscle of the lower limb. Another research explores the relationship between changes in skeletal muscle thickness and the corresponding estimated values of the pennation angle. The focus is on a specific lower limb muscle, the Vastus Lateralis muscle [10]. Moreover, diffusion-tensor magnetic resonance imaging can be employed to investigate the impact of age and muscle strength on the values of the pennation angle in skeletal muscles [11].

Edge detection technique (Canny operator) [12] was used to outliner muscle fiber. However, it is necessary to start with image enhancement before implementing image edge detection to obtain a better result. Another study was presented by Jalborg (2016) [13]. This study used a random transform method to detect the orientation of muscle fibers and lower aponeurosis. The researcher measured the pennation angle of the gastrocnemius muscle but did not compare manual and automatic measurements. The pennation of the soleus muscle of the lower limb was evaluated manually [14]. The most contributing point of this research is a description of the soleus muscle with high architecture variability.

Furthermore, filters were used to improve the contrast of the image and then segment it using the K-means algorithm [14]. As for the other technique, the extraction of ultrasound image parameters for analysis [15]. Moreover, the deep learning method was employed to extract and separate muscle fibers so that we could do a spontaneous evaluation of the angle [16, 17]. However, deep learning with all its networks needs a huge amount of data in order to be able to detect the muscle fibers and calculate the angle resulting from their convergence, collecting these data needs time and accuracy, especially in ultrasound images.

Automated techniques can help improve measurement accuracy and minimize errors. It's worth noting that advancements in image analysis techniques, such as automated algorithms and computer-assisted measurements, are also being developed to enhance the accuracy and reliability of pennation angle measurements. In this work, fuzzy inference techniques are involved in the contrast enhancement, and segmentation of the muscle fiber of the ultrasound images have been involved. Both steps are preprocessing steps and do not require a large number of images to apply [18, 19]. Fuzzy inference techniques do not hunger for data, they work based on importing knowledge interpretation to fuzzy rules, then defuzzification. Hough transform method [20] is a technique primarily used for feature extraction and parameter estimation in image analysis, particularly for detecting lines or other geometric shapes. It is commonly used in computer vision tasks such as edge detection, circle detection, or line detection. In this work, it can be recruited to detect lines of muscle fiber.

The structure of the paper is presented as a brief survey of related topics such as fuzzy contrast enhancement method, fuzzy edge detection method, and Hough transform technique in the same section. The second section includes the proposal technique and experimental outputs, while the third section shows a discussion of these results. The last section is terminated by some concluding remarks and suggestions for further work on the same subject.

2. Materials and Methods

2.1. Related Work

Related work concerns steps, which it is necessary to prepare skeletal muscle images for pennation angle estimation. The fuzzy inference system is the main driver of these steps. It is a smart way that relies mainly on employing fuzzy logic concepts to solve problems by building the appropriate membership function to represent the problem data. Building fuzzy rules through which we find the solution and then using the inverse of the membership function to obtain the outputs that represent the final solutions. In this research, a modern method of fuzzy logic was harnessed to enhance skeletal muscle images that contain specific details that help us in measuring pennation angle.

Contrast image enhancement and edge detection image are two necessary steps to prepare the image for pennation angle evaluation, both steps depend on the fuzzy inference technique [18, 19]. After collecting samples from the images, the fuzzification process is carried out based on the appropriate membership function. Well choosing the parameters of the membership function can give in most cases promising solutions, and then applying the fuzzy rules. Finally, the defuzzification is done to get the result. Through these steps, it is possible to work on improving the image, successively, and specifying the pixels that describe the muscle fibers using two different methods that depend on the same principle as shown in Figure 2 and Figure 3.

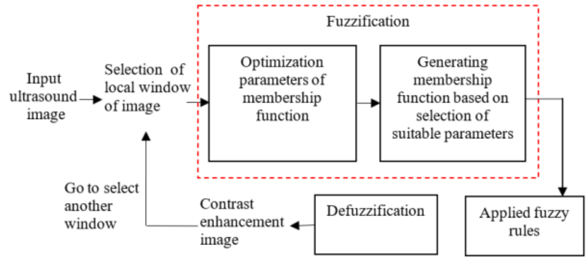


Figure 2. Fuzzy contrast enhancement step [18]

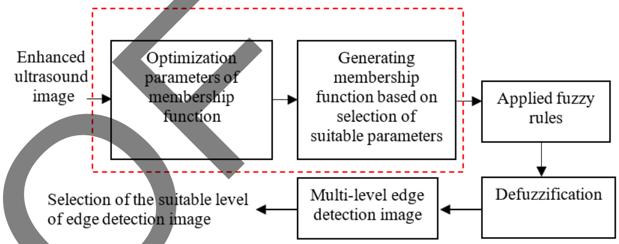


Figure 3. Fuzzy edge detection step [19]

The third step is using the Hough transform technique [20]. It is an effective technique to detect and track several shapes of the image, such as lines, curves, and circles. What concerns us in this work is determining the lines required to calculate pennation angle, so we used this method to achieve this goal. Recently, this technique has been used in the detection of pennation angle of the gastronomes muscle [9, 21].

2.2. Proposed Technique

The proposed technique consists of two parts (Manual measurements and automated measurements), see Figure 4.

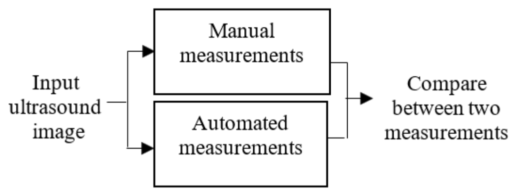
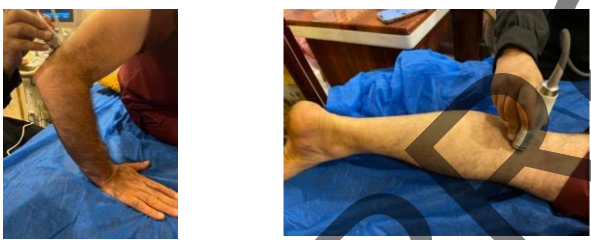


Figure 4. Illustrates the pipeline of the proposed technique

3. Results

3.1. Data Collection (Skeletal Muscle Images)

Data collection in this work represents gathering and measuring information (skeletal muscle images), and it consists of two parts. Firstly, ultrasound images were collected from 20 healthy volunteers (triceps muscles), age range (22-54) years old, and all participants wrote consent letters, this work was based on the (Ref No: ERP1290) from Keele University. In this experiment, we ask the participants to form his/her hand, forearm, and arm in a crab position (see Figure 5) to visualize the longitudinal section of the triceps muscle. Furthermore, the second part of data collection was applied on the gastrocnemius muscle, which is one of the muscles of the lower limb in which 10 healthy volunteer participants, age range of (19-55), were lying on the table as in Figure 5. All volunteers signed letters based on the (Ref No: HMC 26).



a.Upper limb muscle imaging **b**.Lower limb muscle imaging

Figure 5. Presents data collection (skeletal muscle images), *a* shows how can collect skeletal muscle images from the upper limb, while *b* shows low limb muscle image collection

3.2. Manual Measurement

The cumulative experience of the user of the ultrasound imaging device and the technological capabilities of the device play an important role in enriching the manual measurements of the images. Figure 6 illustrates the manual extraction of the pennation angle of triceps muscle as a sample. When manually evaluating the pennation angle of the triceps muscle, tracking muscle fiber orientation from the lower aponeurosis to the upper aponeurosis can be addressed by identifying a straight reference line that intersects with the lower aponeurosis and aligns with the muscle fascicle orientation. However, it is important to acknowledge the limitations of this method and the potential for approximation in capturing the full complexity of the muscle architecture.

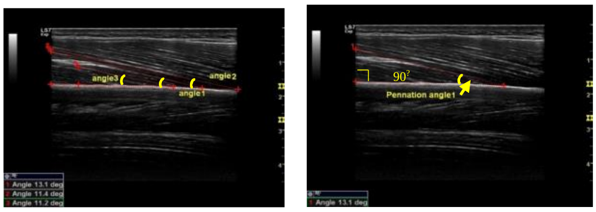


Figure 6. presents the view of the manual pennation angle detection of triceps muscle

The same scenario is carried out on the lateral gastrocnemius muscle to extract pennation angle value, see Figure 7.

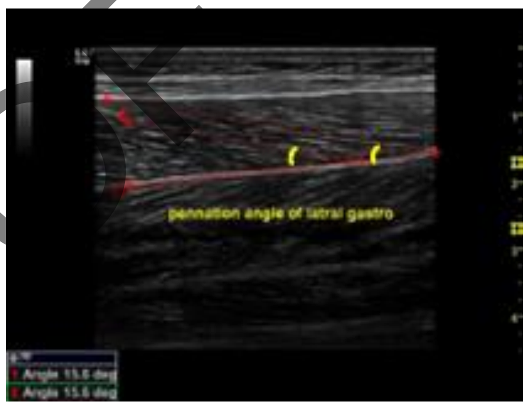


Figure 7. Presents the view of the manual pennation angle detection of lateral gastrocnemius muscle

3.3. Automated Measurement

Accurate tracking of the orientation of the muscle fascicles is crucial for determining the pennation angle. Therefore, ultrasound image needs some pre-processing steps to reach this purpose. The procedural sequence for implementing the initial steps of the proposed technique involves the application of the image contrast enhancement method, followed by the identification of its significant details. These steps are fuzzy contrast enhancement method [18] and fuzzy edge detection images [19] to obtain enhanced image with effective muscle fascicles orientation. Furthermore, the Hough transform method [22, 23], one approach is to identify a straight line that intersects the lower aponeurosis and extends upward to intersect the orientation of the muscle fascicle. This line serves as a reference to estimate the pennation angle. By selecting this line, it becomes possible to measure the angle between the line and the muscle fascicle, providing an approximation of the pennation angle. The sequence of the determination of pennation angle automatically is shown in the Figure below:

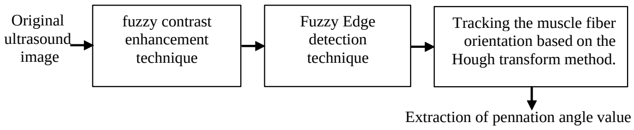


Figure 8. Shows the processing of pennation angle estimation of the triceps muscle

All steps of pennation angle estimation of the (sample 1-triceps muscle) are presented in the Figure below:

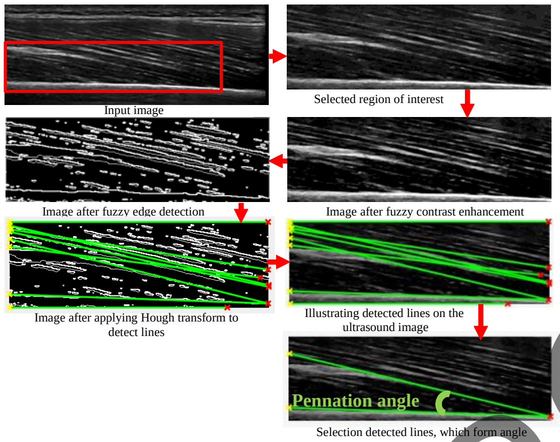


Figure 9. Presents the pipeline of the getting pennation angle value of the triceps muscle

It's crucial to acknowledge that this method presupposes a linear correlation between the lower aponeurosis and the alignment of muscle fibers. Although it offers a pragmatic estimate, it remains an approximation and might not fully encapsulate the intricate nature of muscle architecture. Furthermore, relying solely on a single static snapshot confines the evaluation to a specific moment, potentially overlooking dynamic alterations in pennation angle occurring during muscle contraction or elongation, as illustrated in Figure 10.

The steps of the automated measurements in Figure 10 are applied on the lateral gastrocnemius muscle to extract pennation angle value, see Figure 11. The comparison between values of pennation angles for triceps and gastrocnemius muscles is illustrated in Figure 12. Moreover, statistical descriptions for these measurements based on t-test are presented in Table 1.

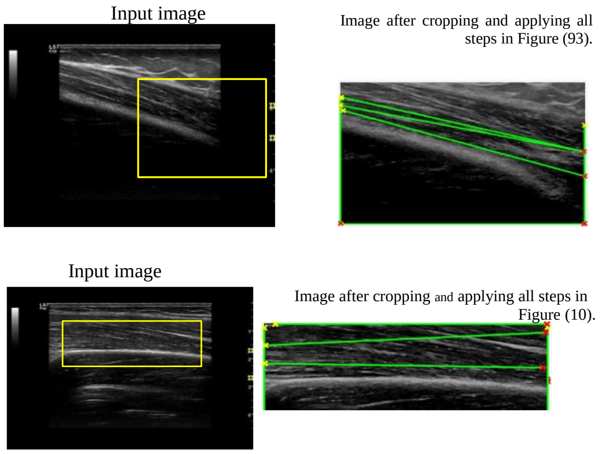


Figure 10. Difficulties in finding a representative line that captures the orientation of the triceps muscle fascicle due to the appearance of the subcutaneous tissue layer

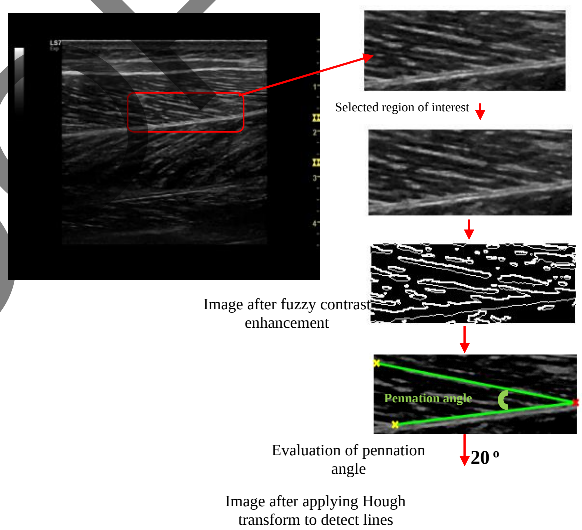


Figure 11. Presents the pipeline of the getting pennation angle value of the lateral gastrocnemius muscle

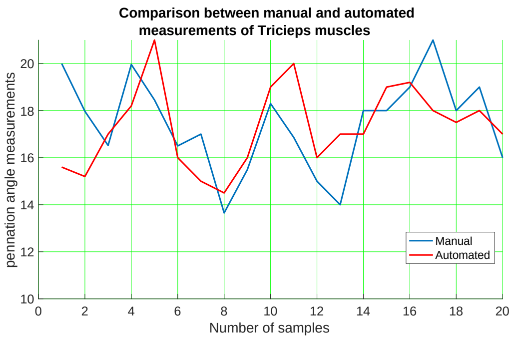


Figure 12a. Presents tracking the differences between automated and manual measurements of triceps

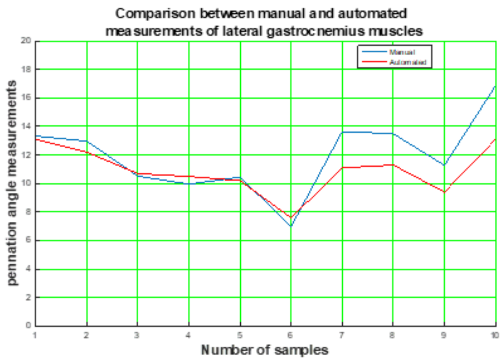


Figure 12b. Presents tracking the differences between automated and manual measurements of lateral gastrocnemius muscles

4. Discussion

In the field of biomedical engineering, musculoskeletal modeling plays a significant role, typically relying on geometric musculoskeletal information extracted from cadaveric studies. While serving as a foundational structure for the musculoskeletal system, this information is time-consuming to acquire and employs non-individualized techniques. Ultrasound imaging presents a valuable alternative, offering patient-specific anatomical data for real-time visualization of muscles, tendons, bones, and other musculoskeletal structures [24]. This paper introduces a novel technique, both manual and automated, for detecting and estimating the pennation angle of muscles using ultrasound imaging.

The proposed technique involves preprocessing steps, such as contrast enhancement and image edge detection, to prepare ultrasound images for accurate pennation angle estimation. These steps contribute to the experiment's objective by improving the precision of muscle fascicle orientation measurement, consequently enhancing the accuracy and reliability of pennation angle evaluation.

Comparing manual and automated methods, the manual assignment of pennation angles is significantly slower, taking minutes, while the automated approach takes only a few seconds. Automated measurements take 85% more time compared to manual measurements.

Additionally, automated techniques offer easier access to results without requiring user expertise, as they follow standardized steps applicable to large datasets. Despite minor differences between manual and automated measurements, statistical analysis indicates that the variations for biceps (upper limb muscle) and gastrocnemius (lower limb muscle) are not significant, with differences of 8.6% and 0.45%, respectively (p-value = 0.416 > 0.05). Furthermore, the main difference lies in the level of confidence and precision associated with each confidence level. From Table 1, a higher confidence level (0.9218) of automated measurements increased the precision of pennation angle value estimation. On the other hand, the manual estimation of pennation angle has 0.8181, suggesting lower precision and a larger margin of error. However, data of manual method was evaluated as more uniform than the automatic method, see Table 1, because it was evaluated as tracking variations of geometric variables of the muscle shape, while the automated method cannot, and therefore it takes 85% more time than the automatic method, where treats all muscles as one case, and it takes a few seconds to calculate the pennation angle.

Table 1. Comparison between automated and manual results

Automatic	Results	Manual	Results
Mean	17.43	**Mean**	17.31
Standard Error	0.44	**Standard Error**	0.39
Median	17.98	**Median**	17
Mode	18	**Mode**	17
Standard Deviation	1.96	**Standard Deviation**	1.74
Sample Variance	3.87	**Sample Variance**	3.05
Kurtosis	-0.37	**Kurtosis**	-0.47
Skewness	-0.25	**Skewness**	0.34
Range	7.35	**Range**	6.5
Minimum	13.65	**Minimum**	14.5
Maximum	21	**Maximum**	21
Sum	348.7	**Sum**	346.2
Time consuming	48 second	**Time consuming**	10 minutes
Confidence Level (95.0%)	0.92	**Confidence Level (95.0%)**	0.81

Moreover, automated measurements not only save time but also exhibit practical advantages. However, limitations arise from the skeletal muscle structure, particularly the presence of subcutaneous tissue on the upper aponeurosis. This subcutaneous tissue, encompassing fat and connective tissue beneath the skin, can impede accurate pennation angle measurements by obstructing the view or complicating precision, see Figure 13. These findings underscore the trade-offs between efficiency and potential challenges associated with the automated approach in the context of musculoskeletal modeling.

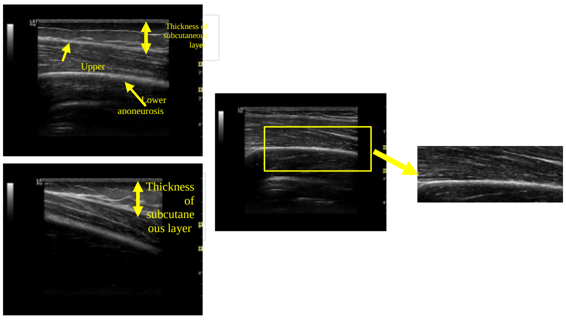


Figure 13. Shows the presence of a subcutaneous layer which can hinder the accuracy and precision of the measurements

5. Conclusion

The automated assessment of the pennation angle presents itself as a dependable and efficient method for the evaluation of muscle architecture. This technique has the potential to either replace or complement traditional manual measurements, introducing a more objective and standardized approach. Notable advantages include heightened accuracy, consistency, and the ability to swiftly process extensive datasets.

Looking ahead, there is a prospect of incorporating panoramic techniques and video imaging for extracting muscle information. This involves slowly moving the ultrasound probe along the muscle length while maintaining consistent pressure, allowing for the visualization of the entire muscle belly. Panoramic imaging, achieved by stitching together multiple adjacent ultrasound images, can create a composite image encompassing the entire muscle.

Moreover, by applying similar ultrasound imaging techniques, the measurement of the pennation angle can be extended to various muscles and tendons throughout the human body. This non-invasive approach holds promise in providing valuable insights into muscle and tendon architecture, functional adaptations, and potential clinical implications.

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