Ultrasound Imaging and Semi-Automatic Analysis of Active Muscle Features in Electrical Stimulation by Optical Flow

Shota Kawamoto, IEEE Graduate Student, Nevrez Imamoglu, Jose D. Gomez-Tames, Kahori Kita, Wenwei Yu

Abstract—**Ultrasound imaging is an effective way to measure the muscle activity in electrical stimulation studies. However, it is a time consuming task to manually measure pennation angle and muscle thickness, which are the benchmark features to analyze muscle activity from the ultrasound imaging. In previous studies, the muscle features were measured by calculating optical flow of the pennation angle by using only fibers of a muscle from the ultrasound, without carefully considering moving muscle edges during active and passive contraction. Therefore, this study aimed to measure the pennation angle and muscle thickness by using the edges and fibers of a muscle in a quantitative way in a semi-automatic optical flow based approach. The results of the semi-automatic analysis were compared to that of manual measurement. Through the comparison, it is clear that the proposed algorithm could achieve higher accuracy in tracking the thickness and pennation angle for a sequence of ultrasound images.**

I. Introduction

Surface Electromyogram (sEMG) is an effective way to measure and assess the activity of surface muscles, but it presents limitations such as signal contamination during electrical stimulation. There are some techniques that can be used to cope with this problem: amplitude threshold to discriminate the EMG from the electrical stimulation signal [1] or comb filter [2] [3]. Nevertheless, stimulation artifacts are difficult to eliminate. Also, intramuscular EMG can be used to measure recruitment in deep muscles; however, invasive approaches have difficulties in obtaining ethical permission.

An alternative method to investigate muscle activity is ultrasound imaging. It has been used since 1950 [4] and provides a non-invasive way to investigate the activityies of both surface and deep muscles in real time. But, ultrasound has to be used with the probe maintaining adequate skin contact and patient's motion is constrained by the probe [5]. In most published studies, muscle thickness and pennation angle (Fig. 1) have been used to measure muscle strength and contraction in voluntary contraction [6], showing that muscle thickness and pennation angle increase during isometric contraction.

In many of those works stated [7] [8], researchers had the measurement manually by checking each ultrasound image on the dataset. However, manual calculation of muscle thickness and pennation angle for ultrasound image sequences takes significant a large amount of time which reduces the efficiency, especially, if there are several ultrasound video data that should be analyzed. Therefore, some studies proposed semi-automatic or automatic algorithms to calculate, measure, and track the pennation angle and fascicle length [9] [10]. For example, in studies [9] and [10], pennation angle and fascicle length were tracked by a method based on the Lucas-Kanade optical flow algorithm with an affine optic flow extension during passive and active motion, but thickness was not considered. The border line of muscle used for measuring thickness is also needed for measuring pennation angle because pennation angle is located between thickness line and angle line. In addition, Zhou et al. [11] proposed a model in which thickness and pennation angle were calculated frame by frame automatically by using Hough Transform. But, in [11], if the ultrasound image is blurred or border line of muscle is difficult to see during movement, border line can't be extracted by Hough Transform, which can adversely affect the analysis of muscle activity in electrical stimulation.

In this study, we tried to improve the optical-flow based measurement [9] [10] by adding the thickness measurement with a semi-automatic approach. First of all, various optical flow algorithms, such as Horn&Schunck (HS) [12], Lucas-Kanade optical flow algorithm with an affine optic flow extension (AF) [13], and refined Pyramidal Lucas & Kanade (PLK) [14] algorithms, were investigated on pennation angle and muscle thickness tracking. The analysis demonstrated that AF performed better on pennation angle, and PLK had higher accuracy on muscle thickness tracking. Therefore, we proposed a simple and fast method by combining two optical flow based models: i) muscle thickness automatically measured by PLK [14], and ii) pennation angle tracked by AF similar to [9] [10]. And, these calculations were done on a dataset that includes muscle movements activity during voluntary contraction and contraction due to electrical stimulation. Experimental results show that the proposed algorithm derives reasonably accurate values at a faster frame rate compared to the manual calculations of pennation angle and thickness.

II. Methods

A. The Semi-automatic Analysis

The Semi-automatic analysis was performed using Matlab R2013a (Mathworks) with Intel® Xeon® E5-2609 (2.40GHz) and 32GB of RAM. A flow chart of the semi-automatic process is shown in Fig 2.

In the first frame of ultrasound data, an examiner manually selected two thickness lines and one angle line for the muscle

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thickness and pennation angle. Then these lines were tracked for all sequential frames by the optical flow-based approach. Horn&Schunck optical flow algorithm (HS) [12], affine optical flow algorithm (AF) [13] and Lucas & Kanade Pyramidal Refined Optical Flow algorithm (PLK) [14] were used to analyze their performances on the calculation of thickness and pennation angle.

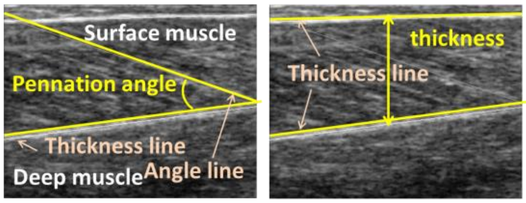


Figure 1. Ultrasound Imaging and muscle features: angle line, thickness line for pennation angle and muscle thickness.

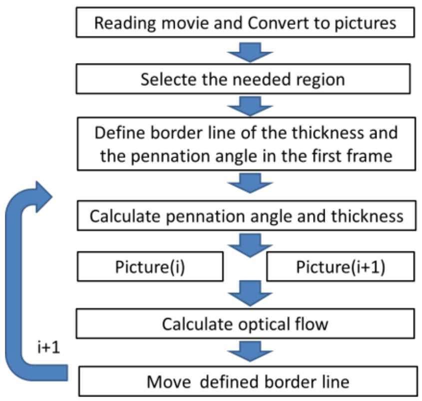


Figure 2. Flow chart of semi-automatic analysis.

Horn&Schunck optical flow algorithm (HS) [12], affine optical flow algorithm (AF) [13] and Lucas & Kanade Pyramidal Refined Optical Flow algorithm (PLK) [14] were selected for the calculation of the muscle thickness and pennation angle. HS is the fundamental algorithm of optical flow calculation. The PLK was selected for its pyramidal implementation taking local features into consideration. To be able to track the lines by HS or PLK based optical flow, points on the defined line were moved along the vector obtained by optical flow calculation, and a new line was generated by using linear approximation on new points, as shown in Fig. 3. The AF can detect the changes about rotation, expansion and contraction of images, expressed by six parameters as in (1): *vxt*, optic flow in *x*-direction; *vyt*, optic flow in *y*-direction; rate of dilation; *r*, rate of rotation; s_1, shear along the main image axis; s_2, shear along the diagonal axis. When AF was applied, pixels (x, y) on the defined line were moved to a new coordinates (x', y') in the image [9].

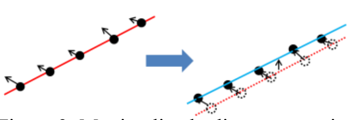


Figure 3. Moving line by linear approximation.

$$\begin{pmatrix} x' & y' \end{pmatrix} = \begin{pmatrix} x & y & 1 \end{pmatrix} \times \begin{pmatrix} \Delta + s_1 & s_2 + r \\ s_2 - r & \Delta - s_1 \\ vxt & vyt \end{pmatrix} \quad (1)$$

Muscle thickness and pennation angle were calculated as below.

Pennation Angle Calculation [15]:

$v_1 = [(x_4\text{-}x_3)\ (y4\text{-}y3)]$; $v_2 = [(x_6\text{-}x_5)\ (y_6\text{-}y_5)]$;

$dp = dot(v_1, v_2)$;

$length_1 = sqrt(sum(v_1.\text{^}2))$; $length_2 = sqrt(sum(v_2.\text{^}2))$;

Pennation angle $= cos^{-1}(dp/\ (length1*length2))$;

Thickness Calculation:

$k_1 = round\ (y_1 + (y_2\text{-}y_1)/(x_2\text{-}x_1)*round\ (c_{middle}\text{-}x_1))$;

$k_2 = round\ (y_3 + (y_4\text{-}y_3)/(x_4\text{-}x_3)*round\ (c_{middle}\text{-}x_3))$;

Thickness $= k_2\text{-}k_1$;

where (x_1, y_1), (x_2, y_2) and (x_3, y_3), (x_4, y_4): the ends of the thickness line, (x_5, y_5) and (x_6, y_6): the ends of angle line obtained by the optical flow based tracking, c_{middle}: the coordinates in the middle of image, *v*: vector of the thickness line and the angle line, *length*: length of the thickness line and the angle line, *dp*: inner product of the thickness line and the angle line, *k*: the *y* coordinates on thickness line in the middle of image.

B. Evaluation of the Analysis

We evaluated the semi-automatic analysis by the correlation coefficient and root-mean-square (RMS) with regard to the thickness and the pennation angle that we measured manually frame by frame. If the manual measurement was consistent in terms of selection of the muscle fiber to measure the pennation angle, as shown in Fig. 4, the muscle thickness and the pennation angle shall be similar.

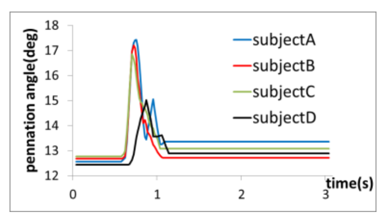


Figure 4. Pennation angles for four subjects by manual calculations. Subject A-C: same muscle fiber was selected, Subject D: different muscle fiber was selected

III. Experiment, Results And Discussion

A. Ultrasonic Measurement

Six male subjects (6 men, age21-23) with no history of neurological abnormalities or musculoskeletal disorders, participated in the experiments. They were informed about experimental procedures and asked to provide their consent.

In this experiment, tibialis anterior muscle (TA) and tibialis posterior muscle (TP) were measured. We recorded ultrasound images of the voluntary contraction (motion 1), the contraction by electrical muscle stimulation (EMS) locating the electrodes directly on the TA (motion 2), and on the lateral area of the knee (motion 3). In order to measure the voluntary contractions, the subjects were asked to sit on a chair and move their toe up and down, as shown in Fig. 5. Measurements were performed three times for each muscle. A pre-modulate electrical stimulation was used in this study with a carrier frequency of 2250 Hz, burst frequency of 30 Hz, and a stimulation duration of 130 ms [16]. The voltage was adjusted for each subject according to their maximum pain tolerance. A square electrode (Axelgaard Manufacturing Co., Ltd, MOFEL 895220) of area 25 cm^2 was employed.

Ultrasound imaging device Aplio™XG (Toshiba Medical Systems) was used at 7.2 MHz, 60 mm field of view, and the images were stored at 60 fps. A holder (Fig.5) for the ultrasound probe ($60 \times 80 \times 50$ mm^3) was developed in order to diminish pressure difference during the measurements. In this study, 2D ultrasound images were recorded, which do not contain the information about out-plane movement, thus may cause the error of be inaccurate to measure real value of pennation angle without out-plane movement. Since the manual measurement used the same 2D image source, we didn't take this as a problem for algorithm evaluation. The probe holder pressure was adjusted until muscle fibers were visible and the pennation angle could be measured in a parallel direction along the muscle under study.

Figure 5. Experiment setup to measure muscle activity.

B. *Evaluation of different optical flow algorithms*

TABLE 1 shows a comparison of different calculation algorithms for optical flow, with regard to motion 1. We removed two datasets as outliers of the experiments since all the algorithms (HS, AF, and PLK) failed to track the features.

TABLE 1. A comparison of different calculation algorithms for optical flow, with regard to the motion 1

Optical flow	**Pennation angle**		**Thickness**	
	correlation coefficient	***RMS***	***correlation coefficient***	***RMS***
HS	-0.18±0.52	3.02±1.07	0.39±0.32	4.44±2.65
AF[9]	0.89±0.09	1.11±0.58	0.49±0.44	3.67±1.46
PLK	0.19±0.56	2.81±1.19	0.80±0.14	1.92±1.00

(16 of 18 datasets)

Because the PLK divides each image into several areas, optimizes local features for each area, and integrates them into a global structure, the thickness line can be tracked more accurately than the HS and the AF.

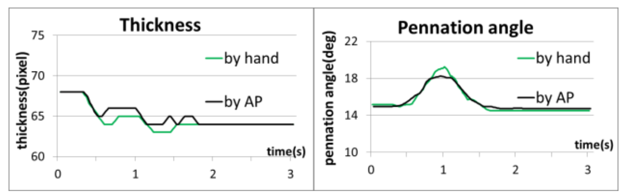
For some frames, the pennation angle was tracked accurately by AF and HS. The pennation angle depends on thickness line and angle line. Regarding the PLK, since the thickness line can be tracked accurately as in muscle thickness tracking, it turned out that the angle line was not tracked stably by PLK. On the other hand, AF had a bad performance in tracking the thickness line, but tracked better the angle line. As the angle line tends to rotate while contracting, AF yielded the best results for tracking the pennation angle by angle line.

TABLE 2. Tracking results of AP (a combination of AF and PLK) with regard to the motion 1

Optical flow	**Pennation angle**		**Thickness**	
	correlation coefficient	***RMS***	***correlation coefficient***	***RMS***
AP	0.79±0.17	1.16±0.62	0.82±0.12	1.81±1.23

(18 datasets)

Therefore, it was made clear that AP algorithm, which is a combination of tracking the angle line by the AF, and tracking the thickness line by the PLK, resulted in the optimal feature tracking compared to using AF and PLK separately, as shown in TABLE 2 and Fig. 6 for motion 1. The muscle thickness by AP is same as by PLK and was tracked accurately. The pennation angle by AP could be tracked more accurately than the other methods because pennation angle was calculated by using thickness line tracked accurately. The AP was used for the remaining experiments.



(a) Thickness (b) Pennation angle

Figure 6. Results of semi-automatic analysis by AP.

C. *Quick motion (motion2, motion3)*

If a subject's leg moves quickly, the holder of the ultrasound probe is likely to slide against the movement, and the images would be blurred. The AP could track accurately for the motion 2 and 3 before the blurred frames occurred. According to the observation of the experiment, blurred images appeared only in quick motions and its influence is especially serious in the first frame of the motion. Moreover, the histogram of a blurred image has a flatter and wider peak than the images of other states (resting, after the onset of a motion), as shown in Fig. 7.

It is clear that, optical flow could not be calculated correctly for the blurred images. In this study, for the frame at the beginning of a motion, the system would send a requirement to relocate the angle line.

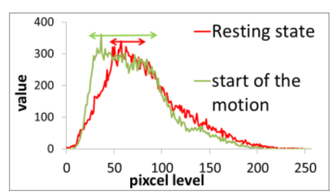


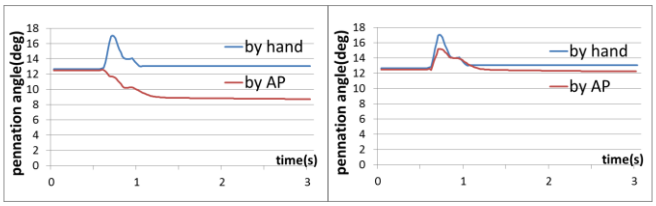
Figure 7. Histogram example of a resting state at the beginning of the motion. Arrows show the even regions.

TABLE 3. Comparing the cases with and without the angle-line relocation with regard to the motion 2 and 3.

Relocation	**Pennation angle**		**Thickness**	
	correlation coefficient	***RMS***	***correlation coefficient***	***RMS***
With	0.86±0.09	0.46±0.20	0.91±0.04	0.72±0.46
W/O	0.72±0.44	1.31±0.64		

(10 of 12 datasets)

The blurred image was detected as follows. A correlation coefficient of histogram between the first frame of the dataset and other frames was calculated. For the frame that has a sudden change in the correlation coefficient, relocation of the angle line was required by the system. Fig. 8 and TABLE 3 show the results with regard to the motion 2 and 3. The muscle thickness was tracked accurately for 10 of 12 cases. Two cases were failed because the thickness line became invisible. It seems that the probe was not fixedly attached and the motion was out of the range of the ultrasound measurement.



(a) Without relocation (b) With relocation

Figure 8. Tracking pennation angle with and w/o relocation

The pennation angle with relocation was more accurate than the case without the relocation. As shown in Fig. 8, in the case without relocation, the correlation coefficient of pennation angle without the angle-line relocation was 0.72±0.44. The peak of the pennation angle in motion was observed to be much lower than the manually extracted true value.

D. Computational costs

TABLE 4 compares the computational costs of different methods and algorithms. The test used a 4-second ultrasound image sequence. The time of AP contains the time of the AF and the PLK. Apparently, the PLK needs a lot of time because of pyramidal calculation, though PLK was calculated only for the required region instead of full image. Since the manual measurement depends greatly on experimenters, average over different experimenter was listed. Apparently, the AP is much faster than manual measurement, however, needs higher computational cost than the other algorithms..

TABLE 4. Comparing computational cost of different methods. (for a 4 seconds data set, containing 120-180 pictures)

Optical flow	***HS***	***AF***	***PLK***	***AP***	***Manually***
Time	20-25 (seconds)	15-20 (seconds)	140-230 (seconds)	160-250 (seconds)	1.5-2 (hours)

IV. CONCLUSION

In order to track the pennation angle and the muscle thickness at a higher accuracy, and at a reasonably lower computational cost, this study focused on the accuracy of optical flow and the error due to quick motion. We were able to track the pennation angle and the muscle thickness faster by utilizing AP than manual measurement. As our future work, we will increase the number of subjects and deal with the ultrasound data containing invisible thickness lines. The out-plane movement of ultrasound measurement shall be taken into consideration.

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