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Ultrasound-Derived Features of Muscle Architecture Provide Unique Temporal Characterization of Volitional Knee Motion

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Abstract—**Sonomyography, or dynamic ultrasound imaging of skeletal muscle, has gained significant interest in rehabilitation medicine. Previously, correlations relating sonomyography features of muscle contraction, including muscle thickness, pennation angle, angle between aponeuroses and fascicle length, to muscle force production, strength and joint motion have been established. Additionally, relationships between grayscale image intensity, or echogenicity, with maximum voluntary isometric contraction of muscle have been noted. However, the time relationship between changes in various sonomyography features during volitional motion has yet to be explored, which would highlight if unique information pertaining to muscle contraction and motion can be obtained from this real-time imaging modality. These new insights could inform how we assess muscle function and/or how we use this modality for assistive device control. Thus, our objective was to characterize the time synchronization of changes in five features of rectus femoris contraction extracted from ultrasound images during seated knee extension and flexion. A cross-correlation analysis was performed on data recorded by a handheld ultrasound system as able-bodied subjects completed seated trials of volitional knee extension and flexion. Changes in muscle thickness, angle between aponeuroses, and mean image echogenicity, a change in brightness of the grayscale image, preceded changes in our estimates of pennation angle and fascicle length. The leading nature of these features suggest they could be objective features for early detection of impending joint motion. Finally, multiple sonomyographic features provided unique temporal information associated with this volitional task.**

Clinical Relevance—**This work evaluates the time relationship between five commonly reported features of skeletal muscle architecture during volitional motion, which can be used for targeted clinical assessments and intent detection.**

I. INTRODUCTION

Ultrasound imaging, or sonography, is a common noninvasive imaging technique for visualizing underlying tissue. Traditionally, musculoskeletal ultrasound involves the use of high-frequency sound waves to image soft tissues and bony structures in the body for diagnosis of pathology or guiding real-time interventional procedures [1]. Many physiatrists employ sonography to inform and provide biofeedback of rehabilitation protocols as well as evaluate muscle and tendon function for its many advantages including the absence of radiation, portability, high resolution of neuromuscular structures and the unique ability to perform dynamic examinations. Research applications of sonography within movement science disciplines has greatly influenced the use of musculoskeletal ultrasound for the characterization of muscle architecture [2], [3].

Dynamic ultrasound imaging of skeletal muscle, i.e. sonomyography, can be used to quantify measures of skeletal (i.e. pennate) muscle morphology and muscle architecture, including muscle cross-sectional area, thickness, pennation angle, fascicle length and angle between aponeuroses during various movement tasks in both healthy and pathological muscle [4]–[7]. Previous researchers have established correlations between changes in these features of skeletal muscle architecture with muscle force production, muscle contraction and resulting joint motion [4], [8]–[10]. Image echogenicity, or image intensity, is related to changes in the acoustic impedance, or density, between various tissues or other materials and has been related to maximum voluntary isometric contraction, as well as muscle quality and muscle strength [11], [12].

Recent developments in ultrasound technology, including miniaturization, increased resolution and higher frame rates, have led to observations that sonomyography is sensitive to fasciculations and is capable of detecting fibrillations of muscle tissue that lead to the actual contraction of muscle fibers [13]. Therefore, sonomyography has the potential to provide physiological features of muscle contraction that can be used as inputs to an intuitive control system for assistive devices. Multiple researchers have evaluated various features, including muscle thickness and fascicle dynamics features, as well as image intensity features to train and test machine learning (e.g., classification and regression models) and neuromuscular model-based control algorithms for both upper- and lower-limb assistive devices [14]–[19].

However, the time relationships between changes in these features of skeletal muscle architecture relative to each other, as well as relative to changes in overall appearance of the grayscale ultrasound image, during volitional limb motion have not been defined. This information can enhance our understanding of the unique features pertaining to muscle contraction and lower-limb motion that can be extracted from a real-time imaging modality, which could benefit researchers and clinicians alike.

The objective of this study was to characterize the time synchronization of changes in rectus femoris image echogenicity and estimates of muscle thickness, pennation angle, angle between aponeuroses and fascicle length

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extracted from ultrasound images during seated (non-weight bearing) knee extension and flexion. *We hypothesize that each of the five sonomyography features will provide differing temporal information during volitional motion.*

II. METHODS

A. *Subjects and Data Collection*

Seven able-bodied subjects (four male, three female; 28.4 mean, 13.7 SD, years old) gave consent to participate in the knee extension/flexion experiment. Subjects were instructed to complete three consecutive cycles of non-weight-bearing knee extension and flexion movements at an isokinetic pace of approximately 45°/second, beginning at 90° knee flexion and proceeding to full knee extension (0°), then returning to 90° knee flexion. Individuals donned a custom-designed 3D printed ultrasound transducer holder placed approximately 60% of the distance between the anterior superior iliac spine and proximal base of the patella [20]. The ultrasound transducer of a handheld and wearable ultrasound scanner (mSonics, Lonshine Technologies Inc) was placed perpendicular to the skin longitudinally over the rectus femoris muscle. A water-soluble gel was applied to the probe to aid acoustic contact and remove the need to directly contact the skin, thus eliminating the deformation of muscle that might occur if increased pressure was applied. The transducer holder ensured a constant orientation of the probe against the skin (Figure 1, left). Standard grayscale ultrasound images were collected in real-time with a transmission frequency of 7.5 MHz and a dynamic range of 50 dB at a sampling rate of 15 Hz (Figure 1, right). A PS-2137 wireless goniometer (Pasco, CA, USA) was used to measure knee angle during the knee flexion/extension movement with a sampling rate of 20 Hz. Participants provided informed consent in accordance with a university IRB-approved protocol prior to participation.

B. *Sonomyography Feature Extraction*

A novel algorithm combined a ridge filter with a random consensus model to estimate four kinematic features of muscle contraction from each ultrasound image frame: muscle thickness, angle between aponeuroses, fascicle length and pennation angle. The ridge filter was used to extract underlying muscular structures in the image and a random sample consensus model was used to segment muscle aponeuroses and fascicles; these methods have been explained in detail elsewhere [21]. Muscle thickness was measured as the mean distance between superficial and deep muscle aponeuroses. Angle between aponeuroses was measured as the angle between the superficial and deep muscle aponeuroses. Fascicle length was measured as the longest detected fascicle by the random sample consensus model. Pennation angle was measured as the angle between the longest detected fascicle and the deep muscle aponeuroses (Figure 2). Image echogenicity, a change in brightness of the grayscale image due to a change in acoustic impedance resulting from a difference in density between tissue or other material, is typically used as a sonographic estimate of muscle quality that has been significantly associated with muscle strength [11]. Therefore, overall mean image echogenicity was extracted as a “kinetic” feature of muscle contraction.

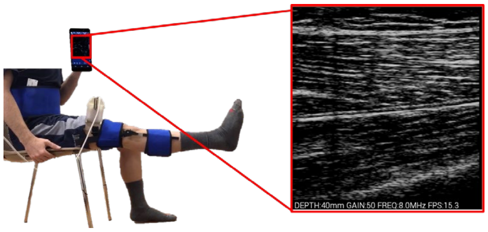

Figure 1. Experimental Setup. *Subject during experimental data collection with portable ultrasound device and goniometer in place (left). Representative ultrasound image of rectus femoris muscle (right).*

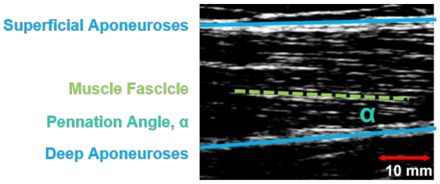

Figure 2. Representative region of interest from raw ultrasound image of rectus femoris with kinematic muscle contraction features labeled.

C. *Timing Analysis of Sonomyography Features*

A time series based cross-correlation analysis was completed to assess time synchronization of these features [22]. The cross-correlation analysis measures the correlation coefficient, r_{xy}, between two signals, x_i and y_i as

$$r_{xy}(l) = \sum_{i=0}^{N-1}(x_i)(y_i). \tag{1}$$

Where l denotes the lag, or the number of data points that the signal y is shifted in relation to x, i refers to each data point in a signal of N total data points. All signals were synchronized to the knee angle data from the goniometer, and trials were trimmed to begin one second prior to knee motion. Sonomyography features were normalized to their respective initial value at the start of the trial, then the normalized initial value was subtracted from all values, such that each signal started at zero.

Data from a single limb of all subjects was included in analyses. Results are presented as means and standard deviations (SD) from all trials of all subjects. A cross-correlation can be considered significant with α of approximately 0.05 when the absolute value of r_{xy} (l) is greater than $\frac{2}{\sqrt{N-|l|}}$, based on a rule of thumb procedure for large-sample normal approximations.

III. RESULTS

The knee angle and all sonomyography feature trajectories were expressed as a function of the trial length (Figure 3). The mean (SD) time for subjects to complete a full extension and flexion trial was 4.58 (1.49) seconds; the mean (SD) range of motion of the extension and flexion was 88.6° (4.6°). The mean (SD) initial values of the rectus femoris muscle features were as follows: muscle thickness of 16.9 (3.21) mm, pennation angle of 11.7° (5.71°), fascicle length of 97.5 (39.5) mm, and angle between aponeuroses of 7.47° (4.36°). The mean (SD) maximum change of muscle features during the knee extension/flexion experiment were: 2.39 mm (0.58 cm) change in muscle thickness, 8.55° (2.45°) change in pennation angle, 73.1 mm (25.3 mm) change in fascicle length, 5.91° (2.12°) change in angle between aponeuroses, and 32.5% (11.3%) change in image echogenicity.

All normalized cross-correlation coefficients proved to be statistically significant given the rule of thumb procedure (Table I). A larger cross-correlation coefficient indicates increased similarity in the time relationship between changes in signals. Unsurprisingly, due to the codependent nature of pennation angle and fascicle length, these signals demonstrated the greatest time correlation. The signals with the lowest time correlation were fascicle length and image echogenicity.

Changes in muscle thickness preceded changes in all other features extracted from ultrasound images of the rectus femoris muscle (negative values in top row of Table II). Additionally, changes in angle between aponeuroses preceded changes fascicle length, pennation angle, and image echogenicity. Image echogenicity, a "kinetic" feature of US imaging of the rectus femoris muscle, significantly preceded changes in both pennation angle and fascicle length. The leading (i.e., preceding) nature of the muscle thickness and image echogenicity and muscle thickness features suggests these could be objective features for early detection of muscle contraction and resulting joint motion. Additionally, there was no time difference (i.e., no lag between signals) between pennation angle and fascicle length.

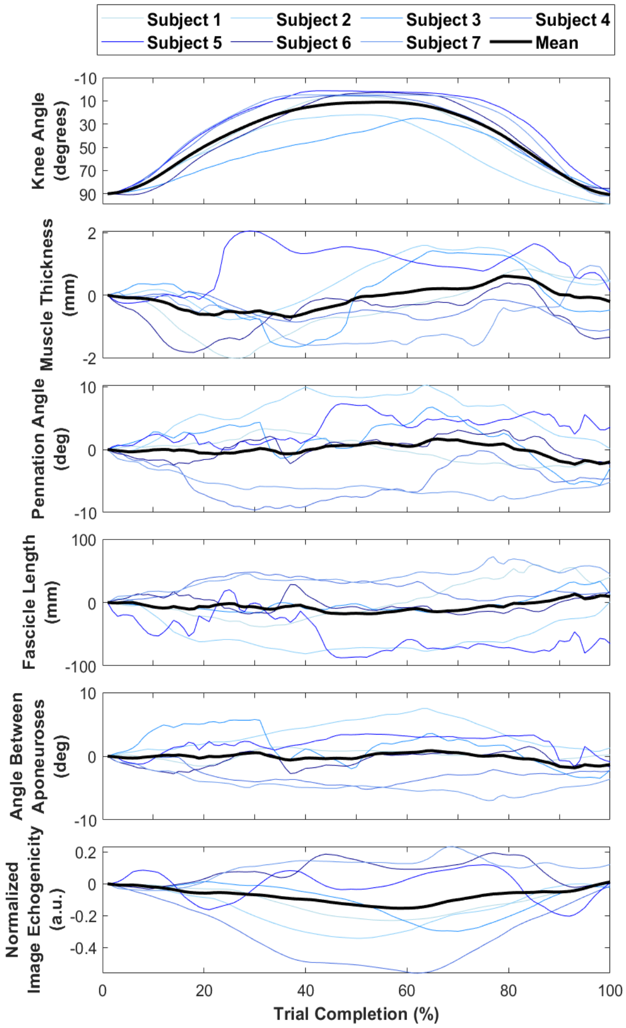

Figure 3. Knee Angle and Change in Sonomyography Features of Rectus Femoris Muscle as a Function of Trial Completion Percentage During Voltional Knee Extension and Flexion. *90° knee angle corresponds to knee flexion and 0° corresponds to knee extension. Blue lines display mean of individual subjects trial data and solid black lines display overall mean of all trials.*

IV. DISCUSSION

We examined the time relationship between changes in multiple muscle architecture and image features of the rectus femoris by sonomyography during volitional non-weight-bearing motion. In support of our hypothesis, the current results indicate a significant time difference between changes of each of the five features: image echogenicity, muscle thickness, pennation angle, fascicle length and angle between aponeuroses. The accessibility of ultrasound technology as well as the recent efforts to increase miniaturization and portability of ultrasound imaging systems has promoted research validating various dynamic ultrasonographic features of skeletal muscle architecture and their correlation with measures of muscle contraction, muscle strength and muscle quality [24], [25].

Our previous work indicated the five features (echogenicity, muscle thickness, pennation angle, angle between aponeuroses, and fascicle length) estimated from the rectus femoris muscle can be used as input to a regression algorithm to accurately predict knee joint angle and angular velocity [21], [25]. The current results give merit to angle

TABLE I. MEAN (SD) (N=7) CORRELATION COEFFICIENT BETWEEN FIVE SONOMYOGRAPHY FEATURES OF THE RECTUS FEMORIS DURING VOLITIONAL KNEE EXTENSION AND FLEXION.

	Pennation Angle	***Angle Between Aponeuroses***	***Fascicle Length***	***Image Echogenicity***
Muscle Thickness	0.75 (0.13)	0.70 (0.16)	0.73 (0.18)	0.74 (0.17)
Pennation Angle		0.78 (0.18)	0.95 (0.05)	0.71 (0.20)
Angle Between Aponeuroses			0.74 (0.20)	0.69 (0.23)
Fascicle Length				0.68 (0.20)

Greater values indicate increased of similarity between signals.

TABLE II. MEAN (SD) TIME DIFFERENCE (SECONDS) BETWEEN FIVE SONOMYOGRAPHY FEATURES OF THE RECTUS FEMORIS DURING VOLITIONAL KNEE EXTENSION AND FLEXION.

	Pennation Angle	***Angle Between Aponeuroses***	***Fascicle Length***	***Image Echogenicity***
Muscle Thickness	-0.54 (0.98)	-0.07 (0.78)	-0.15 (1.33)	-0.60 (1.27)
Pennation Angle		0.30 (1.23)	0.00 (0.05)	0.11 (1.05)
Angle Between Aponeuroses			-0.36 (1.43)	-0.96 (1.80)
Fascicle Length				0.32 (1.43)

Negative values indicate time precedence and positive values show lagging.

between aponeuroses, muscle thickness and image echogenicity as "early" features of muscle contraction and resulting joint motion. Additional features such as pennation angle and fascicle length are highly correlated and provide unique temporal information about muscle contraction during joint motion. Image echogenicity can be detected relatively easily compared to the four kinematic muscle architecture features, which relied on a relatively expensive random sample consensus computational algorithm for extraction. However, less computationally expensive methods could be implemented to improve the applicability of real-time feature extraction [26]. This study suggests that all of these features are favorable for monitoring muscle function and show potential to be used for device control and/or assessment.

There are limitations of the current study that require future research. For example, the non-weight-bearing extension/flexion experiment was performed at a slow speed for each trial and subject. Many volitional tasks occur in a weight-bearing position, and at faster speeds. Although previous work has demonstrated image echogenicity of transverse muscle imaging is a reliable predictor of ambulation mode [27], as well as joint motion and joint torque during ambulation [17], [18], future work is required to determine how the time relationship of the muscle contraction features extracted from longitudinal muscle imaging may change during faster, weight-bearing movements. In addition, the five muscle contraction features were extracted from a bi-articular muscle (rectus femoris) that spans both the knee and hip. To decrease the degrees of freedom of this preliminary study, hip position was relatively fixed in a ~90° flexed (seated) position. These five muscle contraction features will change with variations in both the hip and knee position. Therefore, additional work could evaluate if this time relationship remains in uni-articular muscles and/or during hip and knee motion. Lastly, an evaluation of the reliability of these features across different ultrasound devices would be beneficial.

V. CONCLUSION

The time relationship between five ultrasound-based estimates of rectus femoris muscle architecture during non-weight-bearing volitional knee motion was characterized. The current results indicate muscle thickness, angle between aponeuroses and image echogenicity precede other kinematic features of muscle contraction. There appears to be a strong time correlation between changes in pennation angle and fascicle length. These results support previous work indicating sonomyography is a promising technology for evaluating changes in muscle architecture during volitional motion and muscle contraction for use in rehabilitation medicine with assistive devices.

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