Pennation Angle and Fascicle Length of Human Skeletal Muscles to Predict the Strength of an Individual Muscle Using Real-Time Ultrasonography: A Review of Literature

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Introduction: Muscle fascicle length and pennation angle are two muscle structural parameters which can be non-invasively measured using methods like ultrasonography. The aim of the present literature review was to introduce fascicle length and pennation angle for the estimation of the force of an individual skeletal muscle using ultrasonography. **Methods and Materials**: The data for the current review study was obtained from Pubmed, ScienceDirect, Scopous, Google Scholar, Sprinter Link Database, and other authoritative references available on the Internet and in libraries between the years 1995-2015. A total number of 113 articles were obtained. In sum, 45 articles were collected and reviewed. Keywords such as muscle, fascicle, length, angle, force, and ultrasonography were searched to fulfill the purpose of the study. **Results:** Detailed information on the pennation angle and fascicle length is essential to predict the force of an individual muscle. It has been suggested that changes in muscle fascicle angle and length correlated variably with the muscles force production. **Conclusions:** Real-time ultrasonography has been introduced as a valuable measurement tool for estimation of the force individual muscle via measuring the muscle architecture parameters, such as pennation angle and fascicle length. However, factors like physiological, anatomical, and biomechanical properties have to be considered when predicting the force of an individual skeletal muscle.

Key words: Muscle, Fascicle, Length, Pennation angle, Force, Ultrasonography

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Introduction

Muscle architecture considerably affects muscle behavior and the force transferred to tendons and bones [1, 2, 3]. One of the important parameters for muscle architecture is the pennation angle. Most body muscles form an angle with their aponeurosis and tendon [4]. The pennation angle is introduced as the pattern of arrangement of muscle fibers in relation to the axis of the force generation by the same muscle, which is a major factor in determining muscle performance [5, 6, 7]. In the past, the pennation angle of muscle fibers was measured through autopsy [2], but in this method the values of angles between fibers are changed due to factors such as shortness and also it is not possible to study the effect of muscle contraction and joint condition on muscle architecture. The available imaging methods such as ultrasonography are capable of non-invasively capturing images of muscle fascicles in the static and dynamic contraction states [6].

Precise information on the pennation angle is important to two groups of biomechanical studies. First, it is important for calculating the joint movement based on the prediction of the force generated by the muscle in the direction of its fibers [8, 9, 10] and second, it is important when the force generated in the direction of muscle fibers is calculated [8, 11]. Some of the theoretical models estimate that a change of pennation angle of muscle fibers is a result of the length of variations of muscle fibers during isotonic contractions. In other words, in these models, muscle thickness (the distance between aponeuroses) remains invariant when the muscle fiber increases or decreases in length [12, 13, 14, 15]. However, some researchers have indicated that muscle thickness may change during contraction [16, 17, 18]. Therefore, validity of the results of the assumption about invariant muscle thickness is still approved [13].

Also, another group of researchers have reported that muscle architecture varies during dynamic and even isometric contractions [19, 20]. In a muscle with a transverse cross section and a specific volume, more fibers are juxtaposed in parallel with an increase in the pennation angle, and thus the muscle force generation capacity escalates [21, 22, 23, 24]. In this regard, other researchers have stated that the maximum force generated in a pennated muscle is larger than that in a muscle with parallel fibers, but the same volume and transverse cross section [23]. In an ultrasonographic study on the semispinalis capitis muscle, it was found that muscle thickness varies during contraction from zero to 100% of the maximum isometric contraction of the neck extension force and also there is a good correlation between muscle thickness and force during muscular contraction [18]. However, the neck multifidus muscle only experiences a correlation only up to 50% of the maximum force and following this level muscle dimension does not change [20].

In general, human body muscles are arranged in a range of approximately parallel fibers with zero angles, such as the sartorius, to fibers with maximum pennation angles, such as the short head of biceps femoris. The previous studies have revealed that with an increase in the pennationangle to only 45 degrees both forces (i.e. the force generated in the direction of muscle fibers and the force component transferred to the tendon) escalate [8, 21].

The current survey aimed at introducing fascicle length and pennation angle for estimation of skeletal muscles strength using ultrasonography. To this end, it is first necessary to present general information on ultrasonic measurement of the pennation angle.

Real-time ultrasonographic assessment of muscle performance is a non-invasive method for measuring variations of live muscle architecture at rest and in the static and dynamic states [8, 25, 26, 27, 28]. It allows measurement of pennation angles, fascicle lengths, and specific levels of muscle contraction [4, 8, 25, 26]. B-mode ultrasound can non-invasively capture images of muscle fascicles in the static and dynamic contraction states. In fact, it defines images by processing lightness of images of body tissues. Muscle fibers are shown as dark areas on images, whereas the fascicles look bright [6]. The pennation angle, size, and thickness of muscle may vary by muscular contraction, thus these parameters are proposed for measuring muscular activity using ultrasonography [29, 30].

Ultrasound imaging can be used to determine low levels of muscular activity, and it is also capable of distinguishing between strong and moderate contractions [18, 20, 30]. Ultrasonography is also capable of recording activities of deep muscles regardless of the mutual effects of adjacent muscles [31, 32]. However, the following considerations should be taken into account for ultrasound-based measurement of muscle activity. Firstly, the activity is captured by a change in fiber angle, fiber length, and muscle thickness. Secondly, the relationship between the activity and muscle architecture depends on the type of the muscle due to the properties of series elastic components.

The three-dimensional (3D) ultrasound device or the 3D ultrasound system uses multiple B-mode ultrasonographic images with 3D coordinates of each image to build a 3D shape of an object using a specialized software product [7, 33, 34]. This method allows for 3D measurement of muscle architecture at rest and in the contraction states [7].

Frey *et al.* used 3D ultrasonography to successfully observe the 3D model of skeletal muscles. They stated that the architecture and shape of muscles are shown by these images. However, they only measured the length and thickness of the gastrocnemius muscle at rest [7, 33]. Hiber *et al.* measured the pennation angle of fascicles of the tibialis anterior muscle during contraction using 3D ultrasonography. The authors reported a considerable difference between measured muscular contraction values with a difference coefficient of 30 to 40% [34]. Hence, although 3D ultrasonography is useful for determining variations of muscle architecture during contraction, some of its aspects are still unknown. In a study by Kurihara *et al.*, the validity and utility of 3D ultrasonography in measuring 3D architecture were assessed [7]. They first measured an object with a specific shape and size using 3D ultrasonography and estimated the error level and difference coefficient to ensure validity of measurements. Afterwards, the length of the lateral head of the gastrocnemius muscle was measured at rest and in contraction states using 3D and 2D ultrasonography and the results were compared. Their investigations revealed that the lengths measured using 3D ultrasonography were longer than the 2D ultrasonography values. As compared to the 2D method, this method is capable of analyzing the 3D architecture of human body muscles. Vertical and horizontal errors of 3D measurement were 1.2-1.6% and 0.3-1%, respectively. They also approved the precision and repeatability of 3D ultrasonography in measuring target length in the 3D space. It was considered that 2D ultrasonography and MRI are not suitable for non-invasive observation of muscles at rest and in contraction states as they use the planar imaging or 2D imaging method [7], because fibers inside a muscle are juxtaposed in a 3D space [7, 35, 36, 37, 38]. In this regard, Agur *et al.* indicated that most fibers of the soleus muscle in human corpse are curved and are arranged with inclination [35]. Muramatsu *et al.* reported that there are curved fascicles inside the human gastrocnemius muscle that

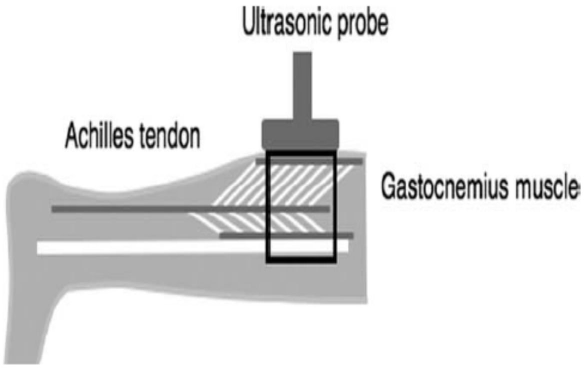

Figure 1. Ultrasound imaging of the fascicle angles of gastrocnemius muscle

change with the degree of contraction and length of fascicles [37]. Therefore, 3D ultrasonography can be useful for completion of the existing information.

To Measure the pennation angle and length of muscle fascicles, the individual is asked to stay in a comfortable position and the probe of the ultrasound is placed on the skin.

The image of the fascicles is shown by the reflection of the ultrasound waves from the muscle (Figure 1) [1]. Then, one of the fascicles in the above image can precisely be followed with movement of the probe on skin surface and the ultrasound image shows the entire fascicle from the beginning to the end. The pennation angle is formed as an angle between reflections of central aponeurosis and muscle fascicles at the connection with aponeurosis [22].

Discussion

Measurement of pennation angle and length of fascicles using 2D and 3D B-mode and real-time ultrasonography is highly useful for depicting and assessing muscular performance, especially at deep layers. Ultrasonography methods for assessment of pennation angle and length of fascicles are based on practical methods for estimation of the force of each muscle during various contractions. Isometric and isotonic methods are employed for comparing muscular contractions at different angles and velocities of ultrasonography.

An example of the previous studies on the relationship between force and pennation angle of fascicles is the research by Maganaris *et al.* who investigated variations of the pennation angle of the tibialis anterior muscle using real-time ultrasonography [22]. They captured images of the tibialis anterior muscle of the right foot at rest and in the maximum isometric contraction states in the following four ankle positions: 15 degrees of dorsiflexion, 0 degree, 15, and 30 degrees of plantar flexion. They observed that with an increase in ankle degree from 15 degrees of dorsiflexion to 30 degrees of plantar flexion at rest and in contraction states, the pennation angle decreased significantly while fascicle lengths increased and thickness remained invariant. Comparisons between the resting and contraction states at each of the mentioned ankle angles indicated an increase in the pennation angle and a decrease in fascicle length with invariant thickness (Figure 2). Later, another study was conducted by Reeves *et al.* to investigate the behavior of fascicles of this muscle during dynamic contractions using ultrasonography [39]. Using a dynamometer, Reeves at al. measured the maximum dorsiflexion isometric torque at 6 ankle angles including 10 and 20 degrees of dorsiflexion, zero degree, and 10, 20 and 30 degrees of plantar flexion. Moreover, using an isokinetic dynamometer, the maximum concentric and eccentric dorsiflexion forces were measured at different angular velocities. They reported that during isometric contractions, the average lengths of fascicles at all ankle angles or during the maximum isometric contraction was significantly smaller than those in the resting state. The average pennation angle at all ankle angles or during the maximum isometric contraction was significantly larger than that of the resting state. By changing the ankle angle and switching from the resting state to the state of maximum isometric contraction, no significant change was observed in muscle thickness. In addition, they found that during eccentric contraction, the length of fascicles at one ankle angle was independent of angular velocity and was not significantly different from that of isometric contraction. The pennation angle during eccentric contraction at all angular velocities was significantly smaller than the same value for isometric contraction whereas the pennation angle did not vary significantly at different angular velocities. The average muscle thickness at all angular velocities during eccentric contraction was significantly larger than its thickness during concentric contraction at similar ankle angles. However, thickness significantly changed with variations of angular velocities. During the concentric contraction, the length of fascicles at similar ankle angles was significantly larger than isometric contractions during concentric contraction at 3.46 and 4.36 Rad/s angular velocities. The pennation angle during concentric contraction at 1.75, 2.62, 3.49, and 4.36 Rad/s angular speeds was significantly smaller than that during isometric contraction at an invariant ankle angle. Moreover, at a constant ankle angle, the length of fascicles of this muscle increased during concentric contraction with an increase in angular velocity whereas the pennation angle dropped [39]. Another study was conducted in the same year by Hodges *et al.* to compare the ultrasonography and Electromyography (EMG) methods in measuring architectural parameters and activities of the leg muscle (calf and tibialis anterior muscle), arm muscles (brachialis and biceps), and abdominal muscles (abdominal internal oblique muscle and transverse abdominal muscle) during isometric contractions at different levels of

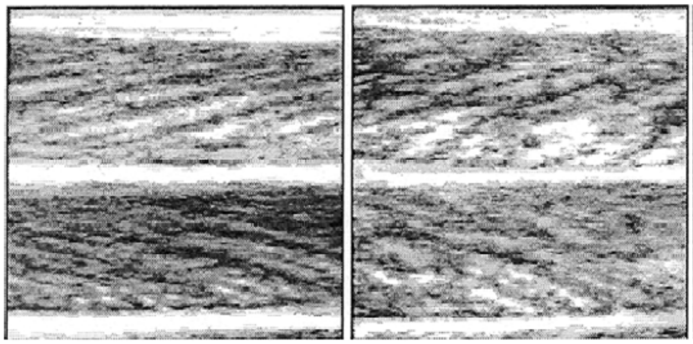

Figure 2. Ultrasonographic image of the tibialis anterior muscle at rest (left image) and in the maximum isometric contraction (right image) states

intensity [30]. They realized that in the tibialis anterior muscle, muscle thickness and pennation angle escalated with an increase in the isometric contraction force, while the length of fascicles decrease nonlinearly. They also stated that during lower than 20-percent of muscle contractions, the maximum variations of each of the ultrasound and EMG parameters were more significant whereas during higher than 50-percent of muscle contractions, variations were more insignificant. The biceps and brachialis muscles also functioned similar to the tibialis anterior muscle with an increase in the isometric contractions. In abdominal muscles, following an increase in the isometric contractions thickness of the abdominal internal oblique muscle and transverse abdominal muscle increased while a nonlinear decrease was observed in the length of the transverse abdominal muscle. These variations occurred following an increase in the contraction level to less than 20% of the maximum force. During low-level of muscle contractions (20-30% of the maximum force), slight changes in muscle activity led to significant changes in muscle architecture. During more powerful contractions, muscle architecture changes dropped relatively. Therefore, the pennation angle changes during muscular contraction as a result of fiber movement and it grows with an increase in contraction force [6]. Consequently, a difference variation between pennation angles at rest and in the state of muscle contraction may be napped [6, 11, 22, 25]. In addition, with an increase in the contraction force and the pennation angle, the length of fascicles may decrease [8, 21, 22, 24].

Pasquet *et al.* investigated the effect of fascicle length variations on motor units and discharge velocity in the tibialis anterior muscle during isometric contractions at different levels of muscle contraction and at the 10 degrees of dorsiflexion and 10 degrees of plantar flexion [40]. They used a computer-controlled ergometer equipped with a foot plate to measure the torque generated in the tibialis anterior muscle during isometric contraction. They also recorded activities of this muscle using a needle and surface EMG. A needle electrode was inserted into the medial part of the muscle and two surface electrodes were placed on both sides of the needle electrode at 2 to 3-cm intervals. Muscle architecture variations were also investigated using ultrasonography at both angles and different contraction levels in a separate session. They observed that the maximum torque along the longer muscle length increased significantly and EMG activity of the muscle decreased significantly with an increase in its length. In the resting and maximum contraction states, the average pennation angle was significantly smaller along the longer muscle length than the shorter length, whereas the length of fasciles along the long muscle length was significantly larger. The average length of fascicles during maximum contraction along the long and short muscle lengths subsided as compared to the resting state, but the pennation angle increased. In addition, the threshold of motor units along the shorter muscle length dropped and the speed of discharge of motor units decreased per unit increase in torque, and the decrease was more considerable along the shorter muscle length. During less than maximum conscious isometric contractions, use of motor units and discharge velocity were higher in short fascicles than in long fascicles [40]. Chauhan *et al.* (2013) studied a regression equation for estimation of muscle thickness and pennation angle at different intensities of EMG during isometric contractions [41]. They simultaneously used an ultrasonography device, EMG, and dynamometer to measure the pennation angle, and thickness, and activity of rectus femoris and vastus lateralis during different degrees of isometric contractions of knee stretching. A total of 55 male football players participated in this research, and the researchers reported a significant relationship between predicted ultrasound and EMG values of rectus femoris muscle thickness. However, no significant relationship was observed between predicted values of pennation angle and EMG activity of the vastus lateralis. They stated that the regression equation functions more precisely for muscle thickness and it can be used to determin variations of contraction intensity. This equation can also be used in skeletal muscle models to estimate muscle force.

Maganaris *et al.* conducted another research on the gastrocnemius muscle to investigate variations of the pennation angle and fascicle length of this muscle at different ankle lengths at rest and in isometric contraction states [8]. They captured images of all the three muscle heads, namely the extrinsic and lateral gastrocnemius and soleus muscles, at rest and in the maximum isometric contraction states at 4 ankle angles including dorsiflexion (15 degrees) and planta flexion (0, 15 and 30 degrees). In all of the three muscle heads, they observed that with an increase in the ankle angle from 15 degrees of dorsiflexion to 30 degrees of plantar flexion at rest and in contraction states, the pennation angle increased

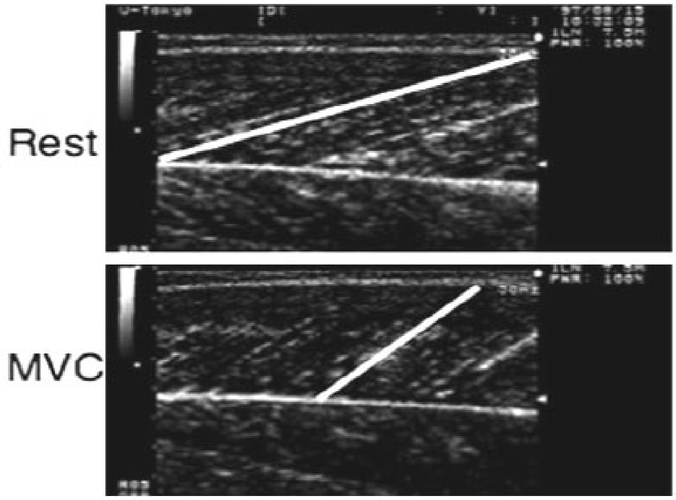

Figure 3. Ultrasonographic images of the gastrocnemius muscle at rest (top image) and in maximum isometric contraction state (bottom image)

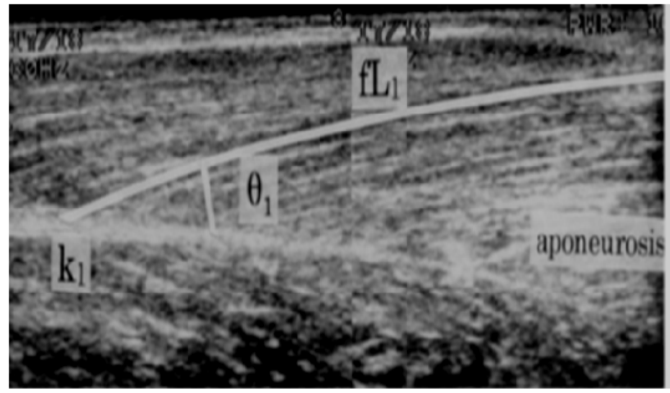

Figure 4. Ultrasonographic images of the vastus lateralis muscle (FL: fascicle length; θ: fascicle angle (the angle between fascicles and deep aponeuroses); and K: fascicle-aponeurosis connection)

significantly whereas the length of fascicles decreased (Figure 3). With an increase in ankle angle, the thickness of extrinsic gastrocnemius muscle and soleus increased significantly during contraction as compared to that in the resting state. However, thickness of the lateral gastrocnemius muscle remained unchanged, and in the comparison between the resting and maximum contraction states at any ankle angle, the pennation angle was larger in all of the three muscles and fascicle length was smaller in all of the three muscles. In addition, Simoneau *et al.* compared architectures of the plantar flexor and dorsi flexor during agonist and antagonist isometric contractions on a certain EMG activity level using ultrasonography and EMG methods [42]. Making use of these devices, they examined the lateral gastrocnemius muscle and tibialis anterior muscle during ascending isometric contraction and concluded that in both muscle groups and on a similar level of EMG activity, fiber length increases and pennation angle decreases during antagonist contractions. In their "discussion", they stated that both groups of muscles produce more mechanical output during antagonist contractions on a certain level of EMG activity, which is important to muscle function tests. They also showed that the antagonist force is underestimated using EMG and net torque relationship.

In 1997, Fukunaga *et al.* conducted a study on the vastus lateralismuscle and length of fascicles and the knee joint angle of this muscle at rest and in a 10% maximum isomeric contraction using real-time ultrasonography device (Figure 4). They captured images of the vastus lateralis at the center of the thigh at rest at different knee angles from the state of full stretching to 110-degree flexion and vice versa, for every 10 degrees. They used an electric dynamometer to determine the resulting torque. Their findings revealed that in the absence of contraction (rest state), as the knee joint angle decreases from 110 degrees to zero degree, the length of fascicles decreased, whereas with static conscious contraction and a 10% maximum contraction at several angles, the length of fascicles dropped. The decrease was higher at smaller angles (before full stretching) and the pennation angle increased with fully stretched knee. At similar angles, the pennation angle during contraction was larger than that in the resting state. There were different relationships between the pennation angle, fascicle length, and knee joint angle at rest and in contraction states. Similarly, with more than 90 degrees of knee flexion, the length of fascicles in the contraction state was partially yet significantly shorter than that of the resting state, but no significant difference was observed in the pennation angle. With a 40-90 degree knew angle, the length of fascicles was shorter during contraction and the pennation angle was somewhat smaller than in the resting state angle. When the knee was stretched with lower than 40-degree angle, the length of fascicles decreased, whereas the pennation angle increased significantly. Therefore, the muscle architectural parameters (such as fascicle length and pennation angle) influenced the muscle functional characteristics such as maximum force and internal parameters such as combination of fibers [2].

Rudroff *et al.* studied the elbow flexor muscles to compare the variations of intramuscular surface EMG and architectural ultrasound findings of the muscle during a submaximal isometric contraction [43]. They used an EMG device (surface and needle electrodes) to examine activity of biceps, brachialis, and brachioradialis during a depressive contraction (MVC 20%). In addition, architectural variations of these muscles were recorded using an ultrasonography device. The authors reported that the needle EMG amplitude did not escalate with the increase in the brachialis thickness and the related pennation angle, whereas an increase in the brachioradialis thickness was accompanied by an increase in the amplitude of one or two of the needle EMG signals. In their discussion, Rudroff *et al.* stated that the failure time was strongly related to the speed of escalation of EMG amplitude as compared to that in the needle type. Therefore, they suggested that surface measurement was more suitable for analyzing variations of muscle activity during depressive contraction.

As an indirect and alternative method to estimate muscle force output, Jizhou *et al.* reported that muscle architecture like pennation structure of medial gastrocnemus correlated well with different levels of MVC while measuring the rate of force development (RFD) (44). The authors stated that muscle ultrasonography can be regarded as a promising option for indirect estimation of muscle force output. Later on, Fukutani and Kurihara revealed that pennation angle and muscle thickness are two validated parameters to compare two groups of individuals with different level of training (45). However, they also reported that fascicle length was not significantly different between the two groups.

Conclusion

Real-time ultrasonography has been introduced as a valuable measurement tool to estimate the force of an individual muscle via measuring the muscle architecture parameters like pennation angle and fascicle length. Seemingly, in some skeletal muscles such as cervical multifidus muscles, an increase in muscle thickness may not be a good estimator of muscle force, especially when the force increases more than 50% of the maximum voluntary contraction. In most of the case, measurements of pennation angles and muscle fascicle length (where possible), may be a good estimator of the force of a human skeletal muscle. However, factors like physiological, anatomical, and biomechanical properties have to be considered when predicting the force of an individual skeletal muscle.

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