

SELECTED MUSCLE ARCHITECTURE CHARACTERISTICS OF THE  
QUADRICEPS AND ADAPTATION TO TOTAL KNEE ARTHROPLASTY

by

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(Under the Direction of Michael S. Ferrara)

ABSTRACT

Muscle architecture has a direct impact on force and excursion capabilities. The use of B-mode ultrasound has proven to be a valid and reliable method of assessing these characteristics in vivo. Muscle thickness (MT), pennation angle (PA), and fascicle length (FL) show adaptation to conditions of muscle enlargement, although the effects of disuse are not clear. Total knee arthroplasty (TKA) is a procedure that is commonly associated with disuse manifested through knee extensor weakness following surgery, and provides a unique model in which to examine the muscle structure/function relationship at the architectural level.

In this study, subjects undergoing TKA (n=14) were compared to controls (n=15) using measures of muscle architecture assessed by B-mode ultrasound. Across a three-month time period (including pre- and post-operative in TKA subjects), no significant group  $\times$  time interactions were observed. Significant angle  $\times$  region interactions were observed for muscle thickness, pennation angle, and fascicle length. Muscle thickness and pennation angle were increased in the proximal muscle region, and at 70°, while pennation angle was increased in the distal muscle region, and at 0°. Lack of adaptation

in muscle architecture characteristics among surgical knees did not correlate with three-month improvements in range-of-motion and Knee Society scores.

Distinct adaptations in muscle architecture were not seen after TKA. These results would predict no changes in force and excursion characteristics in this group of subjects. The use of ultrasound can provide information beyond that of a traditional clinical examination and can be used in rehabilitation to help identify and explain potential areas of muscle weakness.

INDEX WORDS: Muscle architecture, Vastus lateralis, Total knee arthroplasty, Ultrasound

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## DEDICATION

This dissertation is dedicated to my mother, Doris J. Casto, who I continue to learn from every day, and who taught me that quality, not quantity, is what matters most in life

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## CHAPTER I

### INTRODUCTION

Historically, human skeletal muscle has been examined from a microscopic level, using analysis of the various filamentous proteins and other subcellular organelles such as mitochondria, nuclei, satellite cells, sarcoplasmic reticulum, and transverse tubular system (41). Structural properties of these different components have yielded important advances in helping explain muscle function. A renewed interest in the macroscopic level of human skeletal muscle, known as muscle architecture, has emerged in the last decade, utilizing technological advances such as magnetic resonance imaging (MRI) and ultrasonography (US). Muscle architecture can have a direct impact on function (41), excursion (41), and joint integrity (14) as measured by force production and maximal shortening velocity, as well as providing a scientific rationale for surgery (41) and subsequent rehabilitation. The ability to quantify muscle and tendon structure and function is important for understanding how these tissues change with maturation, aging, training, disuse, and disease.

#### **Muscle Architecture**

##### *Variables*

Muscle architecture is defined as the arrangement of muscle fibers relative to the axis of force generation (43). In vivo assessment of architecture using B-mode ultrasound allows for the calculation of four important muscle architecture variables: muscle

thickness (MT), pennation angle (PA), fascicle length (FL), and fascicle curvature (FC). Each variable has a distinct impact on muscle function. Muscle thickness is representative of muscle size (33) and directly influences its force-generating capacity (11). It can also be used to estimate muscle volume (48), from which physiological cross sectional area (PCSA) can be calculated, and has recently been shown to be a valid and reliable measure of cross-sectional area as an alternative to MRI (57). Subjects with substantial muscle hypertrophy have greater muscle thickness than normal controls (2,13,35,36). Increases in muscle thickness are often accompanied by increases in pennation angle (2,13,35,36). Pennation angle is the angle between a fiber (fascicle) and the deep aponeurosis. The concept of pennation and, therefore, increase in pennation angle, allows more contractile material to be packed into a particular area of muscle, compensating for the relative amount of force that is inherently lost with pennation. Pennation angle is directly related to force transmission from the muscle fibers to the tendon (27).

In vivo measurement of muscle architecture does not allow for direct fiber length measurement. Alternatively, this method yields fiber bundle, or fascicle, length indicative of the number of sarcomeres in series (34). The maximal shortening velocity of a muscle is represented by fascicle length. As with pennation angle, there is evidence that suggests fascicle lengthening may be related to the degree of hypertrophy of the muscle (34). Current controversy exists as to whether reported fascicle lengthening is a function of physical training and/or genetic predisposition (4). Both pennation angle and fascicle length are associated with regional differences in oxygenation status of muscle (47). Fascicle curvature has been qualitatively observed in studies of human muscle

architecture (21,27). Greater curvature has been hypothesized to increase intramuscular pressure, with a subsequent reduction in blood flow (62). Positive correlations have been reported between fascicle curvature and pennation angle (50). Muramatsu et al. (50) showed that subjects with larger pennation angle of the *m. gastrocnemius medialis* showed greater curvature, leading to a hypothesized increase in intramuscular pressure. Calculation of fascicle curvature can give an indication of the true length of the fascicle. Estimation of fascicle length is typically performed using the formula:

$$FL = [MT \times (\sin^{-1} PA)] \quad (1)$$

Use of this formula assumes that the fascicle follows a straight path from superficial aponeurosis to deep aponeurosis. Estimation of fascicle length can produce significant errors if the fascicle follows a curved path (50). This error has been reported to be an underestimation of 6% to 7% using the human gastrocnemius, but could possibly be greater in a larger muscle such as the *m. vastus lateralis*. Otten (54) hypothesized that as a muscle shortens, fascicle curving occurs as to induce bulging of the muscle, producing pressure toward the concave side. This theory suggests that the direction of curvature (concave vs. convex) may be different along the length of the muscle, and may change during maximal muscle shortening and lengthening.

## **Measurement Techniques**

### *Microdissection*

True determination of muscle architecture requires a cadaver microdissection approach. Using this technique, traditional muscle architecture variables such as muscle

length, fiber length, sarcomere length, pennation angle, and physiological cross-sectional area can be determined. Muscle fibers undergo shrinkage during the fixation process of microdissection, which has led to the argument that cadaver data may actually underestimate true fiber length (42). Microdissection also does not allow the effects of muscle contraction and changes in joint position on muscle architecture to be studied (21,52).

### *Ultrasonography*

Ultrasonography is both a valid (33,48) and reliable (21,27,33) technique for determination of muscle architecture in vivo. When compared to microdissection, mean ultrasound measurements differ by only 0 mm to 1 mm for muscle thickness and 0° to 1° for pennation angle of various muscles (33). Coefficient of variation (COV) of these measures assessed by ultrasound has been shown to range from 0% to 8% across two consecutive days in literature reports (21). Pilot data in our laboratory revealed within-day COV over two consecutive days to be 0.40% to 1.3% for muscle thickness, 1.4% to 6.7% for pennation angle, and 1.1% to 7.1% for fascicle length. Between-day COV from day one to day two was 0.6% to 0.8% for muscle thickness, 3.4% to 4.5% for pennation angle, and 3.1% to 4.6% for fascicle length.

On the ultrasound image, muscle thickness represents the perpendicular distance between the superficial aponeurosis and deep aponeurosis of a muscle (33). Pennation angle represents the angle between the echo of the deep aponeurosis of the muscle and interspaces of the fascicle (33). FL represents the distance covered by the entire fascicle from superficial aponeurosis to deep aponeurosis (21) and is both a valid and reliable (27) estimate of fiber length. Although fascicle curvature can often be seen on the ultrasound image with clarity, mathematical models have been only recently derived and

implemented to quantify curvature and assess its potential impact on muscle function (50).

### **Total Knee Arthroplasty**

Total knee arthroplasty (TKA) is a common surgical procedure in the United States among adults aged 65 and over, with approximately 300,000 performed annually (67). A majority of individuals electing to undergo the procedure do so because of end-stage arthritis (namely osteoarthritis). During TKA, areas of both the femur and tibia are removed, while metal and plastic components are anatomically and biomechanically situated in their place. Patients generally experience an improved quality of life following TKA (67), although physiological limitations such as decreased strength and function of the knee extensors often persist for many months (8,69). Post-operatively, the initial month appears to be the most critical time for regaining extensor mechanism function (59). Subsequently, decreases in strength (59), volitional activation (9,49,65), and physical function (20) have been shown at this time point. Strength asymmetry between surgical and non-surgical knees has been reported in unilateral TKA subjects post-surgery (8,69).

Muscle strength of the quadriceps femoris (QF) often lags behind the hamstrings during post-operative rehabilitation and, as a result, the hamstrings:quadriceps ratio (H:Q) ratio can show abnormal values up to two years post-TKA (8). Isometric extension and flexion peak torques were shown to be 30.7% and 32.2% lower than control values, respectively, in TKA patients at a mean of 2.8 years post-surgery (63). Current rehabilitation protocols for TKA may not be addressing the appropriate mechanism(s) behind the quadriceps weakness exhibited in this population (65). An understanding of

how tissues adapt to altered usage can result in more appropriate rehabilitation strategies following a procedure such as TKA.

### **Muscle Architecture and Plasticity**

The manner in which muscle architecture adapts to conditions of hypertrophy has been well characterized. Increases in measures of muscle thickness, pennation angle, and fascicle length have been shown in populations that are traditionally associated with muscle enlargement, such as bodybuilders and powerlifters (2,13,33). These groups show correlations between muscle thickness and pennation angle similar to those of normal controls (33). The effects of disuse atrophy on muscle architecture are less clear. Based on models of hypertrophy, measures can be expected to decrease (52). Few studies have examined muscle architecture in disuse atrophy (12,51), and no longitudinal studies have been reported. Patients with lower extremity unilateral bone and/or ligament injuries were shown to have significantly lower pennation angle and fascicle length of the GM compared to the uninjured leg, by 16.4% and 12.7%, respectively (51). Similarly, patients who had undergone interlocking intramedullary nailing for either femur or tibia fractures showed a 27.3% decrease in pennation angle of the VL of the affected limb (15.4° vs. 21.2°) (12). Muscle architecture can be altered as a result of training (1,10,58,60), although the intensity and duration required are typically greater than what is traditionally used in a rehabilitation setting. It is unknown to what extent a rehabilitation protocol such as that following TKA has on measures of architecture. To date, no studies examining pre- and post-TKA muscle architecture have been performed.

## **Purpose Statement**

The purpose of this study was to evaluate how muscle architecture characteristics of the vastus lateralis change over time from pre-operative to 3 months post-operative in TKA subjects, and over a similar three-month period in healthy older adults, using B-mode ultrasound.

## **Hypotheses**

We hypothesized that:

1. Surgical knees will show pre-operative decreases in muscle thickness, pennation angle, and fascicle length compared to non-surgical and control knees (at their first testing session).
2. Surgical knees will show adaptation to values more similar to control values at both the one- and three-month testing sessions.
3. Control subjects will show no change in muscle thickness, pennation angle, and fascicle length across the three testing sessions.
4. Positive correlations will exist between muscle thickness and fascicle length, muscle thickness and pennation angle, and between pennation angle and fascicle curvature.

## **Limitations**

This study was limited by the following factors:

1. The use of a posterior stabilized, single-axis, single-radius design knee implant, which may not reflect results from other types of total knee implants.
2. Inability to follow an entire fascicle from origin to insertion on the ultrasound image.

## CHAPTER II

### REVIEW OF LITERATURE

The significance of examining muscle architecture is found in its relationship to force and excursion capabilities (42). The use of B-mode ultrasound has materialized in the last decade as both a valid (33,48) and reliable (21,27,33) means of assessing muscle architecture in vivo. Muscle thickness, pennation angle, fascicle length, and fascicle curvature of both upper and lower extremity muscles can be calculated using real-time ultrasound-generated images. This method offers advantages over traditional techniques of muscle architecture determination such as cadaver microdissection (23), MRI (41,52,61), and CT scan (42). Muscle architecture has not been studied extensively in disuse atrophy; based on models using muscle hypertrophy, architecture measures can be expected to decline (33). Total knee arthroplasty (TKA) represents a unique model of examining disuse atrophy at the muscle architecture level (8) due to common strength and function deficits post-surgery, but has yet to be studied using ultrasound.

This review of literature is divided into three sections. The first section will introduce the concept of muscle architecture and the role of ultrasound, including validity and reliability. The second section will focus on the architecture measures that can be calculated using ultrasound – muscle thickness, pennation angle, fascicle length, and fascicle curvature. Interpretation of these parameters, as well as their interrelationships, will be discussed. The last section will deal with application of muscle architecture using

ultrasound in specific populations of interest, most notably those involving lower extremity disuse atrophy.

### **Muscle Architecture**

Skeletal muscle architecture is one of the most important properties that determine a muscle's force and excursion capabilities (15,41,42). It is defined as the arrangement of muscle fibers relative to the axis of force generation (43). This arrangement varies greatly between different types of muscles (longitudinal, unipennate, multipennate) and can affect different aspects of muscle function (42). An understanding of the structure-function relationships that define muscle architecture can help explain contractile properties of a muscle (42). Determination of typical architectural parameters can help explain why one muscle is more suited for force production (e.g., VL) as opposed to shortening velocity (e.g., *m. biceps femoris*). Implementation of this information can be especially useful for those studying hypertrophy and/or disuse atrophy, where models of muscle architecture can be formulated and used to potentially explain their etiology and changes which may occur over time (12,33,52). Muscle architecture can also provide a scientific rationale for surgery involving tendon transfer, provide guidance for electromyography electrode placement, help explain the mechanical basis of muscle injury, aid in the interpretation of histological specimens obtained from muscle biopsies (42), and assist with rehabilitation protocols.

#### *Validity and Reliability of Muscle Architecture Determination*

Early pioneers of muscle architecture determination used a microdissection technique that included chemical fixation of muscles while they were attached to the skeleton (43). Fixation was performed to preserve physiologic length, and muscles were

dissected. Measurements of typical architectural parameters – muscle mass, fiber length, muscle length, pennation angle, and sarcomere length – were determined from the dissection. Although this method has remained the standard by which other methods of muscle architecture calculation are measured, it does present inherent limitations (41). Muscle fibers undergo shrinkage during the fixation process, which has led to the argument that cadaver data may actually underestimate true fiber length (42). Microdissection also does not allow the effects of muscle contraction and changes in joint position on muscle architecture to be studied (21,52).

More recent methods, using MRI and ultrasound, have proven to be valid and reliable for measurement of muscle architecture in vivo (21,27,33,48). Kawakami et al. (33) attempted to validate ultrasound measures of muscle thickness and pennation angle in the *m. triceps long-* and *medial-heads* using cadaver data. Average cadaver age was >70 years, while average age for control subjects was 23±5 years. Calculation of muscle thickness derived from ultrasound differed from cadaver measures by only 0 mm to 1 mm, while two consecutive measures of muscle thickness yielded a correlation coefficient of 0.978. Similarly, ultrasound calculation of pennation angle showed only a 0° to 1° difference from cadaver data, with correlation coefficients of 0.947 for *m. triceps long head* and 0.856 for *m. triceps medial head*. Validity of ultrasound-generated muscle thickness as a means of estimating muscle volume in the knee extensors (compared to MRI) was examined by Miyatani et al. (48). Multiple regression analysis was used to predict the percentage of MRI-calculated muscle volume that could be explained by ultrasound-generated muscle thickness in 46 men aged 20-70 years. Muscle thickness explained 75% of the variation in muscle volume measured by MRI, indicating the

usefulness of muscle thickness as an acceptable method for this calculation. As MRI is often costly and inaccessible, ultrasound can serve as an alternative method for muscle volume calculation, from which PCSA can be calculated.

Fukunaga and colleagues (21) examined the coefficient of variation (COV, a measure of reproducibility) of pennation angle and fascicle length of the VL under both relaxed and contracted (10% MVC) conditions in six healthy men. The COV was determined using the equation

$$\text{COV} = (\text{SD} / x_c) \times 100 \quad (2)$$

where SD was the square root of the between-test variance obtained from the one-way repeated measures analysis of variance, and  $x_c$  was the combined mean of measurements obtained on two separate occasions. The COV of pennation angle measured every 10° from full extension to 110° ranged from 0% to 2% relaxed and 0% to 3.8% contracted; fascicle length COV ranged from 0% to 6.8% relaxed and 0% to 6.1% contracted. The changes in COV were not affected by changes in knee joint angle. The small values of COV and lack of statistical difference between measurements attest to the reproducibility of these measurements.

## **Measures of Muscle Architecture**

### *Variables*

Three common variables are typically reported in studies examining in vivo muscle architecture determined by ultrasound, each playing a distinct role in helping to explain muscle function. The first, muscle thickness, is often the easiest variable to calculate. It is defined on the ultrasound image as the perpendicular distance between

superficial and deep aponeuroses (33), which normally are quite distinct. The aponeuroses are compliant tendon structures that, along with tendons themselves, comprise the major source of the series elastic component (38). Muscle thickness is indicative of muscle size (33), is correlated with cross sectional area (57) and hypertrophy (33), and can be used to estimate muscle volume (48). The second variable, pennation angle, represents the angle created by fibers with respect to the muscle's force-generating axis (41,42). It is represented on the ultrasound image as the angle between the deep aponeurosis and the interspaces of the fascicles (33). A pennate muscle, containing fibers not oriented perpendicular to the force-generating axis, is not able to transmit all of its force to the tendon during muscle movement and is characterized by an inherent loss of force (42). Consequently, pennation accounts for this loss of force by allowing many more fibers to "pack" into a particular muscle area, increasing the amount of contractile tissue. The original drop in force is completely accounted for, and exceeded, by the increased packing ability. An increase in pennation angle allows physiological cross sectional area (PCSA) to greatly exceed anatomical cross sectional area (ACSA), thereby increasing force-generating capacity (1). Pennation angle tends to change as a function of muscle thickness in many muscles; in the VL, increases in muscle thickness have been correlated with increases in pennation angle (33).

Fascicle length is representative of the number of sarcomeres in series (34) and is one component that characterizes a muscle's maximal shortening velocity (along with myosin ATPase activity and the load placed on the joint) (2,34). It is visually defined on the ultrasound image as the absolute length of a fascicle, from superficial to deep aponeurosis. A longer fascicle length may be associated with an ability to generate

greater muscle joint torque (3,34). A relatively long fascicle, which could share shortening distance between its sarcomeres, could potentially shorten at a slower velocity than a relatively short fascicle (3). Each sarcomere would therefore shorten a smaller distance than in short fascicles (i.e., the shortening distance is shared). This physiological occurrence could place the longer fascicle at a stronger portion of the sarcomere force/velocity curve, implying greater force-generating capacity (3).

The entire length of a fascicle can be seen on the ultrasound image in certain muscles; muscles with longer fascicles (such as the VL), as well as equipment limitations, often make visualization of the complete length impossible. Thus, an estimation formula has been developed as a means of calculating fascicle length. This formula has been used extensively used in the literature and has a reported COV of 4.7% (3). If muscle thickness and pennation angle are known, basic trigonometry can be used to determine fascicle length (recall equation 1):

$$FL = [MT \times (\sin^{-1} PA)] \quad (1)$$

This estimation, however, is based on the assumption that the fascicle follows a straight path from origin to insertion. This assumption does not always hold true, as qualitative accounts of fascicular curvature (21,27) as well as quantitative accounts (45,50) have been reported. Muramatsu et al. (50) calculated an average fascicle length underestimation of approximately 6% (in the GM) if curvature is not taken into account, which could possibly be greater in a larger muscle such as the VL (27).

While traditional architectural parameters of muscle thickness, pennation angle, and fascicle length are routinely reported, fascicle curvature is typically ignored. Curving of fascicles has been reported qualitatively (21,27); however, few studies have attempted to quantify this potentially important architectural feature. Fascicle curvature has been defined as the reciprocal of the radius of a circle ( $1/r$ ) (50) and, similar to other muscle architecture variables, plays a part in determining the functional capabilities of a muscle (45,50,62). A curved fascicle exerts a force in the direction of curvature, while the magnitude of this force is proportional to the curvature (62). As a result, intramuscular pressure is increased (62). Otten (54) proposed that as a muscle shortens the fascicles become thicker, forcing the central portion of the muscle to bulge in an onion-like configuration and increasing pressure in this part of the muscle. This bulging is due, in part, to the fascicle curvature.

Fascicle curvature can have important physiological implications. Consider a muscle with great curvature (small  $r$ ). This muscle would transmit little stress to the tendons, and most stress would be reflected as intramuscular pressure. A muscle whose fascicles are primarily straight (large  $r$ ) would be expected to develop little pressure; fascicle stress could be directly measured as contraction force of the whole muscle. Sejersted et al. (62) have reported that contraction pressures in the central portion of the muscle will be higher when greater fascicle curvature exists than when fascicles are stretched with the same stress. As curvature is hypothesized to be greatest in short muscles, intramuscular pressures would be highest in conditions of curvature during free movement. Therefore, short, bulging muscles may have shorter endurance times than

those with long proportions at the same contractile stress. The longer muscles would develop less intramuscular pressure so that blood flow is better maintained.

In vivo calculation of fascicle curvature as determined from ultrasound has been reported only in the GM to date. Muramatsu et al. (50) presented a mathematical model of fascicle curvature calculation based on the assumption that the fascicle was one arc of a circle with radius  $r$ . The validity of this model was tested as the fascicle length, calculated from curvature, was compared to fascicle length traced on the ultrasound image and also to an estimation equation. The curvature-based fascicle length showed no difference from the traced length; however, the use of the estimation equation produced an approximately 6% smaller fascicle length than the other two methods. Mean values for fascicle curvature ranged from  $0.2 \text{ m}^{-1}$  to  $0.6 \text{ m}^{-1}$  at rest and  $4.0 \text{ m}^{-1}$  to  $5.9 \text{ m}^{-1}$  at MVC. Significant, positive correlations were found between fascicle curvature and pennation angle in both the distal ( $r=0.9$ ,  $p<0.05$ ) and central ( $r=0.77$ ,  $p<0.05$ ) portions of the GM. These regions also produced significant, positive correlations between fascicle curvature and muscle thickness ( $r=0.84$  and  $r=0.9$ , respectively, both  $p<0.05$ ). Fascicles curved in the same direction throughout the muscle at both rest and contraction, which coincides with the proposals by Sejersted (62) and Otten (54) that the direction of curving was different in proximal and distal portions of a muscle, producing the onion-like configuration during contraction. The mathematical model proposed by Muramatsu et al. (50) was also used by Maganaris et al. (45) to examine repeated contractions of the GM (10 successive isometric contractions @ 80% of MVC). Average fascicle curvature was found to be  $4.3 \text{ m}^{-1}$ , which corresponded well to the values of Muramatsu et al. (50). This

variable was not affected by contraction number (i.e., values for curvature did not change from the first to tenth contractions).

The use of ultrasound to calculate muscle cross-sectional area (CSA) can be traced back nearly 40 years (29), although its more extensive use in muscle physiology research has been limited until recently. The first cited report of ultrasound in determination of muscle architecture in vivo was by Henriksson-Larsen et al. (24). The method was initially thought of as an advantageous alternative to CT scanning, in that length recordings are easily made, and ultrasound waves are reflected from collagen-rich fascia septa between fascicles (making visualization of muscle easier). Images from relaxed and contracted VL muscles were obtained from 15 females at approximately 10 cm proximal to the upper border of the patella. Pennation angle during the relaxed condition ranged from 8.5° to 17.5° and from 17.0° to 25.5° during contraction. In addition, a significant, positive correlation ( $r=0.816$ ,  $p<0.05$ ) was noted between pennation angle and fascicle length. Measures of fascicle length varied between 75 mm to 155 mm relaxed, and 50 mm to 95 mm contracted. As we will see, this initial attempt at in vivo measurement of muscle architecture using ultrasound yielded values that remain consistent with more recent data.

Although Henriksson-Larsen et al. (24) studied muscle architecture during contraction, the level of this contraction was not specified (i.e., percent of MVC). This particular technique was established by Fukunaga et al. (24) in a landmark study. Pennation angle and fascicle length of the VL were examined in six healthy men in both relaxed and contracted (10% MVC) conditions. The uniqueness of the study was reflected in the analysis of muscle architecture throughout the range of motion (every 10°

from  $0^\circ$  to  $110^\circ$ ), allowing graphical representation of patterns as the knee moves from flexion into extension. Both pennation angle and fascicle length showed very distinct patterns as a function of knee joint angle. Fascicle length decreased as the knee was moved from flexion ( $110^\circ$ ) into full extension ( $0^\circ$ ) in both relaxed and contracted conditions (range: 132.9 mm to 96.7 mm relaxed, 128 mm to 70 mm, contracted). Relaxed conditions exhibited higher fascicle length at every knee joint angle than contracted conditions; this difference was significant at every angle except for  $110^\circ$ . An inverse relationship was noted between fascicle length and pennation angle; from flexion into extension the angle increased, again in both conditions (range:  $14^\circ$  to  $18^\circ$  relaxed,  $14^\circ$  to  $20^\circ$  contracted). Larger angles were found in the contracted condition when the knee was in lesser amounts of flexion ( $<40^\circ$ ); these differences were significant at  $0^\circ$ ,  $10^\circ$ ,  $20^\circ$ , and  $30^\circ$ . Collectively, this information gives great insight as to how both relaxed and contracted muscle operates as a function of muscle architecture as a function of joint angle.

#### *Muscle Architecture Distribution*

An important consideration in understanding muscle architecture is its distribution throughout a particular muscle. The majority of published reports have examined architecture characteristics at the mid-point of a muscle (i.e., 50% of the distance between proximal and distal ends); however, whether these values are indicative of patterns in other areas of a muscle is not well understood. Reports of selective hypertrophy in response to training have suggested that assessment of muscle architecture should be performed in more than one region to ensure that changes are not missed (10). This information can potentially be important following a procedure such as TKA, due to the

extreme distal portion of the QF being manipulated intra-operatively (25). To date, muscle architecture characteristics evaluated along the length of a muscle by ultrasound have not been assessed. Scott et al. (61) showed that pennation angle of 14 muscles within a cadaver thigh differed considerably along the length of each muscle, as measured by MRI. The vastus medialis, in particular, exhibited a 5° angle at its most proximal end, and 50° at its most distal end. These large differences were accompanied by constant fascicle length. Uniformity of fiber (fascicle) length was noted in 27 cadaveric muscles examined by Wickiewicz et al. (70) using traditional microdissection techniques. Pennation angle also showed little difference in different regions of muscle. Although these results suggest that consistency in muscle architecture may exist within different parts of a muscle, the large variation seen in pennation angle measured by MRI raises the possibility that measures of architecture can be distributed in a non-uniform manner throughout muscle. The inherent difficulties associated with using cadaver data in these studies also cannot be underestimated.

Regional architectural differences in the GM associated with changes in oxygenation status were recently reported by Miura et al. (47). Oxygen saturation measured during exercise by functional near infrared (NIR) was significantly lower in the distal portion of the muscle compared to the proximal portion ( $p < 0.05$ ). Greater decrements in fascicle length and increases in pennation angle of the distal muscle region were observed, suggesting greater curvature and intramuscular pressure development in this region compared to the proximal region.

## **Application**

### *Aging*

Limited data are available with respect to muscle architecture as a function of age. Kubo et al. (39) recently demonstrated declines in muscle thickness and pennation angle of the VL that negatively correlated with advanced age ( $r = -0.44$ ,  $p < 0.001$  and  $r = -0.50$ ,  $p < 0.001$ , respectively). These results were supported by Narici et al (53), who observed significant decreases in ACSA (decrease of 19%,  $p < 0.005$ ), muscle volume (25.3%,  $p < 0.001$ ), fascicle length (10.2%,  $p < 0.01$ ), pennation angle (13.2%,  $p < 0.01$ ), and PCSA (15.2%,  $p < 0.05$ ) of the GM among adults aged 70 to 81. Differences in plasticity among muscles can help explain the significant declines in muscle architecture variables, as can differences in daily activity levels between muscles and age-associated reductions in physical activity (39,53).

A positive correlation ( $r = 0.64$ ) has been noted between muscle thickness and pennation angle in individuals of advanced age, suggesting that pennation angle is a function of the relative state of muscle enlargement in this population (as with younger subjects) (39). Of interest was the fact that fascicle length was not associated with age-related changes in any of the muscles examined by Kubo et al. (39), in which fascicle length was scaled to limb length. As fascicle length has been shown to be altered with training (13,35), one might hypothesize that decreased muscle strength and mass would produce decreased fascicle length in advanced age, as shown by Narici et al. (53). Possible explanations for this decrease include a loss of sarcomeres in series at both proximal and distal ends of fascicles (51,53) and a reduction in the average operating length of the sarcomeres (45). The reductions in muscle volume and fascicle length

reported by Narici et al. (53) suggest that sarcopenia results in a loss of sarcomeres both in parallel and in series.

### *Hypertrophy*

Conditions of hypertrophy have been shown to cause significant differences in muscle architecture when compared to normal control subjects. Increases in muscle thickness, pennation angle, and fascicle length have been noted with hypertrophy in both trained and untrained subjects (2,13,33). In certain populations where isolated muscle enlargement is common such as soccer (36), football (2), powerlifting (13), bodybuilding (33), and sumo wrestling (35), increases in muscle thickness of the VL range from 20 mm to 130 mm ( $p<0.05$ ) when compared to control subjects. Kawakami et al. (33) observed significant increases in pennation angle ( $33^\circ$  vs.  $16^\circ$ ) for the *m. triceps brachii* long head ( $p<0.01$ ), but not for the VL, between highly trained bodybuilders and control subjects. The increase in pennation angle would cause more contractile material to be attached to the tendon, which would allow for increased muscle volume and consequently PCSA. Increases in both muscle thickness and pennation angle have been positively correlated ( $r=0.33-0.57$ ,  $p<0.05$ ) in conditions of hypertrophy (13,35,33). Interestingly, no increase in pennation angle was found in the VL of sumo wrestlers; rather, the increased muscle thickness was accompanied by a corresponding increase in fascicle length (100.1 mm vs. 69.7 mm,  $p<0.0001$  vs. controls) (35). In this instance the greater fascicle length appeared to limit the degree of change in pennation angle associated with muscle enlargement, attributed to a training adaptation (35).

### *Atrophy/Disuse*

Much less is known about the effects of disuse on muscle architecture. Models of muscle architecture changes due to disuse are based on those of hypertrophy; muscle disuse should cause subsequent deficits in architecture measures just as hypertrophy results in increased values (52). Ultrasound has been used to examine both actual and experimental models of skeletal muscle disuse. Changes in the GM following unilateral bone/ligament injury were observed in vivo using ultrasound by Narici et al. (51). ACSA, pennation angle, and fascicle length were found to be significantly lower ( $p < 0.001$ ) in the injured leg compared to the uninjured by 23.1%, 16.4%, and 12.7%, respectively. Changes in pennation angle were highly correlated ( $r = 0.96$ ) with changes in ACSA. This internal rearrangement of fascicle length represented a loss of sarcomeres in series that, together with the decreased pennation angle, tended to mitigate the loss of force due to a decrease in contractile tissue.

Disuse atrophy involving the QF following interlocking intramedullary nailing (due to isolated unilateral diaphyseal fractures of the femur or the tibia) was studied in vivo using ultrasound by Bleakney and Maffulli (12). Subject age in this study was more similar (maximum age 82 years) to what would be seen with TKA than in the study by Narici (maximum age 41 years). Post-operative time was not given, although architecture measurements were made an average of 7.6 months post-injury. A significantly lower pennation angle was found in the VL of the nailed compared to the unnailed limb ( $15.4^\circ$  vs.  $21.2^\circ$ ,  $p = 0.0002$ ). A significant difference was also found for fascicle length between the nailed and un-nailed limbs ( $p = 0.0002$ ); the correlation between these two changes was significant ( $r = -0.51$ ,  $p = 0.001$ ). In addition, CSA of the rectus femoris was

significantly lower in the nailed limb, implying that the entire quadriceps muscle was affected.

### *Muscle Architecture Adaptation to Training and Rehabilitation*

Changes associated with muscle hypertrophy have raised speculation as to whether muscle architecture can be altered as a result of training and/or rehabilitation programs. To date, no studies have examined the impact of structured rehabilitation on muscle architecture. In healthy control subjects, pennation angle of the VL was found to increase 35% ( $8.0^\circ$  to  $10.7^\circ$ ,  $p < 0.01$ ) following 14 weeks of progressive, heavy resistance training (1). Intensity of the exercises ranged from 3 to 10 maximum repetitions, 4 to 5 sets per session, and consisted of back squats, incline leg presses, isolated knee extensions, hamstring curls, and calf raises. In addition, quadriceps ACSA (obtained at mid-femur) increased 10.2% ( $77.5 \text{ cm}^2$  to  $85.0 \text{ cm}^2$ ,  $p < 0.001$ ). These findings allowed PCSA (and therefore maximal force-generating capacity) to increase approximately 16% after training.

Using leg extension (machine) exercises, Rutherford and Jones (60) examined quadriceps muscle architecture following 12 weeks of training. Each session consisted of four sets of six repetitions at a weight that could be lifted six times. Pennation angles of the VL and *m. vastus intermedius* showed no significant changes after training, whereas increases in MVC (12.8%), ACSA (4.7%), and MVC/CSA (7.7%) were found. A significant shift in both optimal fascicle angle ( $70^\circ$  to  $60^\circ$ ,  $p < 0.05$ ) and optimal fascicle length (83.7 mm to 93.2 mm,  $p < 0.01$ ) following 14 weeks of training was recently reported by Reeves et al. (58). Elderly subjects performed leg extension and leg press exercises, with VL muscle architecture being evaluated using B-mode ultrasound.

Physical training can result in adaptations in muscle architecture by hypothesized mechanisms such as attainment of a critical pennation angle (13,35) and genetic predisposition (4). Two recent studies (13,35) observed pennation angle that increased in proportion to the degree of muscle thickness increase for all muscles studied except the VL. It is possible that this mechanism continues until a critical pennation angle is reached, increasing tension on the muscle tendon. The normalizing force from the tendon acts as a stretching force on the fascicles, inducing growth. As fascicle length increases, pennation angle decreases, relieving the tension on the fascicles from the tendon. The *m. triceps brachii* long head and GM did not behave in this manner, and exhibited increases in pennation angle as well as increases in fascicle length, suggesting that the critical pennation angle had not been reached.

The topic of genetic predisposition in relation to muscle architecture adaptation was recently addressed by Abe (4), who studied architecture characteristics of monozygous twin pairs. This population was deemed ideal for determining the influence of environmental factors, independent of any genetic effect. Differences reflected within these pairs of twins should be due to environment, being that they contain the same genetic profile. Muscle architecture of the medial and lateral gastrocnemius was examined in nine pairs of monozygous twins; each pair consisted of one who had participated in high-level athletics, one that had not. Significant intrapair resemblance was found in the lateral gastrocnemius for fascicle length ( $r=0.98$ ,  $p<0.01$ ), pennation angle ( $r=0.94$ ,  $p<0.01$ ), and muscle thickness ( $r=0.94$ ,  $p<0.05$ ). Similar results were found in the medial gastrocnemius for pennation angle ( $r=0.73$ ,  $p<0.05$ ) and muscle thickness ( $r=0.86$ ,  $p<0.01$ ), but not for fascicle length ( $r=0.66$ ,  $p>.05$ ). These results suggest that

environmental factors are the predominant factor determining a muscle's architecture. The lack of intrapair resemblance in fascicle length of the medial gastrocnemius raises the possibility that this parameter may be influenced by external factors.

### **Total Knee Arthroplasty**

TKA is primarily an elective procedure that is performed on approximately 300,000 patients in the United States each year (67). It is an invasive procedure that involves cutting away areas of both the femur and tibia and replacing them with metal and plastic implants. The surgery is associated with an improved quality of life, although deficits in strength and function can persist for months and years following the procedure (8,69). Rehabilitation following TKA usually begins with continuous passive motion that is begun within hours of the procedure. After an inpatient period of approximately 3 to 4 days, most patients are discharged on supervised home therapy for approximately 4 weeks. During this period, emphasis is placed on elimination of pain and recovery of strength and function, namely of the extensor mechanism.

#### *Strength and Functional Recovery Following TKA*

Data that describe strength and functional characteristics of TKA subjects in the first weeks following surgery are lacking. Decreases in physical function (20), volitional activation (65), force per cross sectional area (56) and strength (59) have been reported approximately 30 days post-operative. Isokinetic (60°/s) and isometric (90° knee flexion) quadriceps extensor torque has been shown to decrease at three months post-operative (compared to baseline), peak at six months post-operative, and decrease again slightly at one year post-operative in both unilateral and bilateral subjects (64). This finding occurred even though mean velocity (m/s) and stride (m) significantly increased from pre-operative to three

months post-operative (64). Peak isokinetic quadriceps extensor torque (60°/s) was also evaluated in 68 unilateral subjects by Berman et al. (8). Values showed little change from pre-operative to three-to-six months post-operative (26.21 vs. 28.90 ft-lbs), with peak changes seen at seven-to-twelve months post-operative (37.21 ft-lbs). At 24 months post-operative, the surgical knee demonstrated peak extensor torques that were 83% of the non-surgical knee, whereas peak flexor torques were nearly equal between the knees.

Total work (J) was found to be decreased in 29 unilateral and bilateral TKA subjects measured at angular velocities of 90°/s (24%) and 120°/s (26%) one-year post-surgery (69). Although the non-surgical knee produced greater total work than the surgical knee, a deficit persisted when comparing to the control knee. Non-surgical knees attained 87% of total work produced by control knees at 90°/s, and 90% at 120°/s. In contrast, no differences in extensor mechanism normalized EMG signals between surgical and non-surgical knee were found in 10 unilateral patients tested at a mean of 23 months post-operative (25). Both surgical and non-surgical knees of the TKA subjects, however, differed from control subjects at both angles examined. This could be the result of a learned adaptation that led to the symmetrical use of legs in the TKA group post-surgery, or perhaps that the rehabilitation programs may have strengthened both legs equally. It did not appear that any injury the VL may have incurred during surgery contributed to a muscle imbalance or extensor mechanism complications post-operative.

## CHAPTER III

### METHODS

#### **Participant Information**

The study was comprised using two groups; an experimental/TKA group (n=14), and a gender-, age-, and height-matched control group (n=15). Subjects in the TKA group were initially recruited during the pre-operative visit to Athens Orthopedic Clinic, P.A. (approximately one to two weeks before the scheduled surgical date). Males and females aged 20 and older, scheduled for primary unilateral or bilateral TKA in the next six weeks were eligible to participate. This group consisted of nine unilateral and six bilateral subjects. Criteria for exclusion in the study included those with previous joint replacement of the hip or knee and those with neuromuscular disease that might compromise testing protocols and/or results. All surgeries were performed by the same orthopedic surgeon (OMM) and subjects in this group received medical clearance from both their family physician and orthopedic surgeon before study participation.

Control subjects were identified from a cohort of older adults who had engaged in previous studies at the Aging and Physical Performance Laboratory at the University of Georgia. These individuals were chosen based on independence, lifestyle, and overall health. Exclusion criteria were the same as for surgical subjects, including no known chronic joint disease. After a control subject had been identified and appropriately matched to a TKA subject, a clearance form was sent to the individual's family physician

for final medical approval. All subjects included in the study read and signed an Informed Consent Form approved by the Institutional Review Board at the University of Georgia.

### **Study Design**

Muscle thickness, pennation angle, and fascicle length of the VL were determined at three separate time points for all subjects in the study. Fascicle curvature of TKA subjects was also assessed at each time point. TKA subjects were examined approximately one to two weeks pre-surgery, and at one- and three-month periods post-surgery. Control subjects were tested over a three-month period at similar intervals as experimental subjects. Once a TKA subject had completed a respective testing session, the same session was scheduled for the control. Bilateral B-mode ultrasound images were obtained in two different positions of the knee joint (0°-supine, 70°-sitting), and at two locations on the VL (proximal, distal). In addition, range-of-motion (ROM) measurements and Knee Society (KS) Scores were assessed for all subjects at each time point. Ultrasound images were analyzed for measures of muscle architecture using both commercially available and custom-designed computer programs.

### *Protocol*

Each testing session consisted of a systematic order in which data were collected. Subjects were first asked to lie supine on the examining table for ROM measurements to be taken. Active- and passive-ROM (flexion, extension) of the knee joint was assessed bilaterally. The same, standard manual goniometer was used in all cases, with the same examiner making all measurements. These were performed twice per limb, with mean values being used for further analysis. If the two measures were not in good agreement (i.e., within 5° of each other), a third measure was performed. Next, bilateral KS scores

were obtained (30). These scores consist of both clinical and functional sections, each worth a maximum of 100 points. The clinical score is based on pain, ROM, and stability, with point deductions for flexion contracture, extension lag, and severe alignment problems. The functional score is based on a self-report of walking distance, as well as the quality of stair-climbing ability. Deductions within the functional score are given for the use of aids such as canes, crutches, or walkers.

Following this, B-mode ultrasound images were obtained using the technique of Kawakami et al. (33). A water-soluble gel was used as a medium between the ultrasound probe and the subject's skin, providing a means of transmission for the ultrasound wave. Bilateral images of the VL were taken at two positions: knee extension (0°) supine and knee flexion (70°) seated. For each position, a proximal image was taken at 50% thigh length, measured from the greater trochanter of the femur to the lateral femoral condyle (33). A distal image was also taken at approximately 2 to 3 cm from the distal insertion of the aponeuroses into the tendon (11). For each position, the subject was asked to fully contract the muscle, and the mediolateral width was visualized. One-half of this width was used as an approximate position for each measurement. The probe was placed transversely on the subject's skin for initial determination of on-screen landmarks. The probe was then turned longitudinally, in plane with the VL muscle fascicles. From this probe location, the superficial aponeurosis, deep aponeurosis, and VL muscle fascicles were identified. Two images for each testing condition/probe location (0° proximal/distal, 70° proximal/distal) were paused on-screen and saved for further analysis. Criteria for saved images included visual certainty of a fascicle insertion with the deep aponeurosis

(for measurement of pennation angle), and clear outlines of superficial and deep aponeuroses and reference points.

### *Instrumentation*

All muscle architecture measures were obtained using a GE ultrasound unit (Logiq 400 CL, 6.6 MHz array) capable of delivering B-mode (brightness-mode) images. A 546-L, 6.6 MHz transducer was used for all subjects.

### *Data Analysis*

Each ultrasound image was analyzed for measures of muscle architecture using manual determination of muscle thickness, pennation angle, and fascicle length using Scion Image (Scion Corporation, Frederick, MD) for image reduction. Standard definitions for each variable were assigned (33). Muscle thickness (MT) was defined as the perpendicular distance between the superficial and deep aponeuroses. For this measure, the subcutaneous adipose tissue-muscle interface and the intermuscular interface (between the VL and *m. vastus intermedius*) were determined, and the perpendicular distance between the two was accepted as being representative of muscle thickness. The angle between the echo of the deep aponeurosis of the VL and the echo from interspaces among the fascicles was measured as the pennation angle. Due to the inability to visually follow a fascicle from origin to insertion, an estimation formula (recall equation 1) was used to calculate fascicle length (FL):

$$FL = [MT \times (\sin^{-1} PA)] \quad (1)$$

This method of obtaining fascicle length has been used extensively in the literature and has a reported coefficient of variation (COV) of 4.7% (3). Measures of muscle thickness, pennation angle, and fascicle length were calculated three times per image, with mean values used for further analysis. To test the reliability of all procedures used to evaluate muscle architecture, pilot data (n=9, age 24.14±5.7 years, height 174.71±7.7 cm, weight 66.90±10.4 kg) were collected in this laboratory. Within-day COV over two consecutive days ranged from 0.4% to 1.3% for muscle thickness, 1.4% to 6.7% for pennation angle, and 1.1% to 7.1% for fascicle length. Between-day COV from day one to day two was 0.6% to 0.8% for muscle thickness, 3.4% to 4.5% for pennation angle, and 3.1% to 4.6% for fascicle length.

A second method of analysis involved a proprietary computer program (Quick Basic V4.5) used to calculate fascicle curvature. Curvature was defined as the reciprocal of the radius of a circle ( $1/r$ ) (50). The program used four manually digitized points on each fascicle (directly on the ultrasound image) to calculate fascicle curvature. It was assumed that the fascicle shape was an arc (50); thus, the radius of the arc did not change along the length of the fascicle. The fascicle was divided into chords based on all possible combinations of the digitized points, and slope and y-intercept of each chord were calculated. A perpendicular line bisecting each chord was generated. To determine the center point of the arc, the common intersection points of the perpendicular distances were derived by solving simultaneous equations and averaged. The radius was determined by calculating the length between a specific digitized point and the center point of the arc. Hence, the angle of curvature ( $1/r$ ) was calculated. See Appendix A for a

representative diagram and explanation of the steps involved in the calculation of fascicle curvature.

### **Statistical Analysis**

Statistical analysis was performed using SPSS<sup>®</sup> Version 11.5 for Windows (SPSS Inc., Chicago, IL). Descriptive statistics (means  $\pm$  standard deviations) were calculated for demographic variables and all muscle architecture variables. Paired samples T-tests were performed to determine the differences between surgical and non-surgical knees for selected demographic variables. Surgical, non-surgical, and control knees were analyzed for within-group differences across the testing sessions using a mixed model repeated measures analysis of variance (testing session  $\times$  angle  $\times$  muscle region), with the main interest being the interactions between time and group, testing angle, and muscle region. If an interaction was evident, polynomial contrasts were used to detect where the differences existed. A Bonferroni adjustment was used to correct for the family-wise error rate. Simple effects were calculated if a significant interaction was found. A Pearson correlation was performed to determine the relationships between muscle architecture variables. The significance level was set at  $p < 0.05$ ; when contrasts were used, the significance level was set at  $p < 0.0125$  to correct for the family-wise error rate.

## CHAPTER IV

### SELECTED MUSCLE ARCHITECTURE CHARACTERISTICS OF THE QUADRICEPS AND ADAPTATION TO TOTAL KNEE ARTHROPLASTY<sup>1</sup>

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<sup>1</sup>Casto SR, KK McCully, MS Ferrara, KJ Simpson, JK Petrella, TL Kinsey, OM Mahoney. To be submitted to *Medicine and Science in Sports and Exercise*.

## **Abstract**

**Purpose:** The use of B-mode ultrasound is a valid and reliable method of calculating muscle architecture in vivo. Architectural properties such as muscle thickness, pennation angle, and fascicle length reflect force and excursion characteristics and have been well characterized in healthy controls and other populations. Data describing changes and adaptations in disuse atrophy, however, are limited. The purpose of this study was to assess these characteristics in total knee arthroplasty (TKA), a condition that is generally associated with disuse of the knee extensors. **Methods:** Muscle architecture of TKA subjects (n=14) and control subjects (n=15) was assessed over a three-month period (pre-operative, and one- and three-months for TKA subjects; corresponding time intervals for controls). B-mode ultrasound was used for assessment of muscle architecture variables. **Results:** In TKA subjects, neither the surgical nor non-surgical knee showed changes in muscle architecture across testing sessions. Control knees also showed no differences in these measures across testing sessions. In each group, differences were seen as a function of both testing angle (0°, 70°) and vastus lateralis muscle region (proximal, distal). By three months post-operative, surgical knees demonstrated increased range-of-motion and Knee Society scores above pre-operative levels. **Conclusions:** No changes in force and excursion of the vastus lateralis would be expected in these study groups based on muscle architecture results. The use of B-mode ultrasound can provide information beyond that of a traditional clinical examination that can be used to potentially explain changes in strength, force, and activation. **Key words:** MUSCLE ARCHITECTURE, VASTUS LATERALIS, TOTAL KNEE ARTHROPLASTY, ULTRASOUND

## **Introduction**

Muscle architecture represents the arrangement of muscle fibers, which affects conversion of the force and excursion of muscle fibers into joint actions (5). It can be used to identify and characterize different aspects of function, such as force-generating capacity and maximal shortening velocity (9). Using real-time ultrasound, specific architecture variables can be determined that can potentially assist in explanation of muscle function: muscle thickness (MT), representative of the size of the muscle (8); pennation angle (PA), often used to characterize force production; fascicle length (FL), indicative of maximal shortening velocity; and fascicle curvature (FC), which is potentially related to intramuscular pressure and blood flow. These variables have traditionally been determined using alternative techniques such as cadaver microdissection and magnetic resonance imaging (MRI), which are either invasive or expensive (9). Muscle fibers undergo shrinkage during the fixation process of microdissection, which has led to the argument that cadaver data may actually underestimate true fiber length (9). MRI is often costly and inaccessible. The use of B-mode ultrasound provides a non-invasive, inexpensive, valid (8,12) and reliable (5,6,8) determination of muscle architecture.

Disuse atrophy resulting from orthopedic surgical procedures has not been adequately evaluated at the muscle architecture level. Muscle thickness, pennation angle, and fascicle length have been shown to decrease following orthopedic procedures for bone/ligament injuries and fractures of the tibia and femur (3,15). Fascicle curvature has not been examined in disuse atrophy. However, its proposed relationship with intramuscular pressure and blood flow could impact muscle endurance (10,11,14,20).

Muscle atrophy of the knee extensors is frequently encountered in patients with osteoarthritis and subsequent total knee arthroplasty (TKA) (1,24), a procedure performed on nearly 300,000 individuals in the United States each year (23). A majority of patients will also have limited range-of-motion and decreased strength of the knee extensors following TKA, properties that can persist for many months and years (1,24). Current TKA rehabilitation protocols are often inferior in intensity and duration and fail to adequately address these issues (21). The use of muscle architecture in post-operative rehabilitation can provide information other than that obtained clinically and, therefore, assist in individualizing protocols based on the functional needs of the patient.

Data regarding the potential application of muscle architecture measures following TKA surgery are lacking. The purposes of this study were to: 1) evaluate how muscle architecture changes both before and after TKA (in both surgical and non-surgical knees), and 2) evaluate muscle architecture in an age-, gender-, and height-matched group of control subjects. We hypothesized that: 1) the muscles in the legs with surgical knees would have reduced muscle thickness, increased pennation angle and decreased fiber (fascicle) length compared to non-surgical and control legs prior to surgery, and 2) muscles with surgical knees would show significant improvements in muscle thickness, pennation angle and fiber length one and three months post-surgery.

## **Methods**

Fifteen older adults with degenerative osteoarthritis and scheduled for primary unilateral or bilateral TKA were recruited from a local orthopedic clinic. Potential subjects were free of previous joint replacement of the lower limbs as well as any neuromuscular condition that might impact the results. They were contacted by telephone

after their medical history had been reviewed. The same orthopedic surgeon (OMM) performed all cases and cleared all subjects before inclusion in the study. All procedures used a subvastus approach and were cementless, posterior-stabilized, and patella-resurfaced. Overall, 20 surgical knees in eight unilateral and six bilateral subjects and 8 non-surgical knees in the eight unilateral subjects were used for analysis of muscle architecture. One subject withdrew midway through the study and was not used.

Fifteen apparently healthy older adults were matched on age, height, and gender and recruited to participate in the study as control subjects. These subjects were in healthy condition and had no known chronic joint disease of the lower limbs. A medical clearance form was sent to the individual's family physician to be signed before the subject could participate. All participants (TKA and control) reviewed and signed an informed consent form approved by the Institutional Review Board at the University of Georgia, Athens, Georgia. A total of 30 knees were tested in the control group.

#### *Post-Operative Care*

All TKA subjects received standard care physical therapy. Continuous passive motion (approximately 0° to 45°) was begun immediately post-operative while still in the hospital, which was continued until the following morning. Subjects performed inpatient physical therapy (2 times per day) for approximately 3 days. Weight bearing, walking and stair climbing were initiated as tolerated. Specific exercises implemented during this time included ankle pumps, quad sets, heel slides, terminal knee extensions, and straight leg raises. Occupational therapy was also used to assist patients with regaining confidence in performing activities of daily living. Following discharge, patients received home-based physical therapy for approximately 3 weeks (approximately

3 times per week), with an emphasis on range-of-motion and regaining strength and function. All subjects had the option of continuing therapy in an outpatient facility after home-based therapy had been completed.

### *Study Design*

Subjects in both groups completed three testing sessions. Those in the TKA group were scheduled for the first session approximately two weeks prior to surgery. The second and third testing sessions took place at approximately one- and three-months post-surgery. After a session had been completed for a TKA subject, the same session was scheduled for the matched control subject. Time intervals between sessions were approximately the same for both TKA and control subjects.

### *Clinical Assessment*

Bilateral range-of-motion measurements and Knee Society scores (7) were determined for each subject at each testing session. Both active- and passive-range-of-motion measures of the knee joint (flexion and extension) were taken twice per side, with mean values being used for analysis. All range-of-motion measures were taken using a standard goniometer and taken by the same investigator. Clinical and functional Knee Society scores were determined for each subject at each session, both consisting of a maximum of 100 points (7). Clinical scores were based on pain, joint stability, and range-of-motion, while functional scores were based on self-reports of walking distance and stair-climbing ability.

### *Muscle Architecture Measurements*

B-mode (brightness-mode) Images of the *m. vastus lateralis* (VL) were obtained with a commercial ultrasound unit (Logiq 400CL, 6.6 MHz linear array probe , GE

Medical). All subjects were tested in two positions corresponding to knee joint angles of 0° (supine), and at 70° (sitting). Subjects were asked to relax as much as possible during testing. At each of these positions, bilateral ultrasound measurements were obtained. Each knee was examined at both a proximal portion of the muscle, corresponding to 50% of the distance from the greater trochanter of the femur to the lateral femoral condyle, and a distal portion taken at approximately 2 cm to 3 cm from the distal insertion of the aponeuroses into the tendon (2). The ultrasound protocol followed that of Kawakami et al. (8). The mediolateral width of the vastus lateralis was visually inspected following a maximal contraction, and the approximate midpoint was used for all measurements. An ultrasonic gel was placed on the probe as a means of transmission, and the probe was placed longitudinally on the specific muscle area (i.e., proximal/distal) for identification of bony landmarks and accurate placement. The vastus lateralis was identified, and different features were visualized as reference points: superficial and deep aponeuroses, femur, and the vastus intermedius. Figure 4.1 shows an image from a representative subject, indicating the muscle architecture variables and reference points. For each condition, two images were obtained and saved for analysis.

#### *Data Analysis*

All images were analyzed for measures of muscle thickness, pennation angle, fascicle length, and fascicle curvature. An image analysis program (Scion Image; Scion Corporation, Frederick, MD) was used to calculate architectural measures from the ultrasound image. Visually, muscle thickness was defined as the perpendicular distance between superficial and deep aponeuroses; pennation angle was defined as the angle between the echo of the deep aponeurosis of the vastus lateralis and the interspaces of the

fascicles; and fascicle length was defined as the distance from fascicle origin to insertion (11). The program did not allow for on-screen calculation of fascicle curvature. Fascicle length was estimated using the formula  $FL=[MT \times (\sin^{-1}PA)]$  due to the fact that the entire fascicle could not be followed on-screen. A limitation of this estimation is its assumption that the fascicle follows a straight line throughout its length. However, previous studies have reported muscle fascicles to have a nonlinear shape (5,6,10,14). To account for this limitation, a proprietary QuickBasic™ computer program was designed to calculate the magnitude of fascicle curvature using four manually digitized points on the fascicle. For calculation of fascicle curvature, it was assumed that the fascicle shape was an arc (14). The fascicle was divided into all possible combinations of chords based on the four digitized points, and slope and y-intercept of each chord were calculated. A perpendicular line bisecting each chord was generated. To determine the center point of the arc, intersection points between all combinations of pairs of perpendicular lines were calculated by the method of solving simultaneous equations, then averaging the intersection points. The radius (R) was determined from the point of fascicle attachment to the estimated center point of the arc. The angle of curvature (1/R) was then calculated.

#### *Statistical Analysis*

Statistical analysis was performed using SPSS® Version 11.5 for Windows (SPSS Inc., Chicago, IL). Paired samples t-tests were performed to determine the differences between surgical and non-surgical knees for selected clinical measures. Analysis of between-group differences across testing sessions was performed using a mixed model repeated measures analysis of variance (testing session  $\times$  testing angle  $\times$  muscle region, with repeated measures for testing angle and muscle region), with the main interest being

the interactions between time and group, testing angle, and muscle region. If an interaction was evident, polynomial contrasts were used to detect where the differences existed. A Bonferroni adjustment was used to correct for the family-wise error rate. The significance level was set at  $p < 0.05$ ; when contrasts were used, the significance level was set at  $p < 0.0125$  to correct for the family-wise error rate.

## **Results**

### *Descriptive Characteristics*

Descriptive characteristics of the study groups are shown in Table 4.1. Overall, no significant differences were observed between TKA subjects and controls for all participant characteristics except for mass. TKA subjects had 33% greater mass than controls at the pre-operative session. A weight change score was calculated from the pre-operative to three-month testing sessions; TKA subjects showed a mean weight loss of 3.88 kg compared to a weight gain of 0.25 kg for controls ( $p = 0.057$ ) from the pre-operative to the 3-mo. session.

### *Clinical Measures*

Active and passive knee joint range-of-motion was lower in surgical knees than non-surgical and control knees at each time point (Table 4.1). Values for these variables in surgical knees were decreased at one-month post-operative (by  $6.0^\circ$  and  $13.8^\circ$ , respectively), but by three months exceeded pre-operative levels. No differences in clinical and functional Knee Society scores were found between surgical and non-surgical knees pre-operatively (Table 4.1). The surgical knees of TKA subjects showed significant increases in clinical and functional Knee Society scores at one- and three-months post-operative compared to pre-operative (clinical: 68.36, 85.07, 92.08;

functional: 56.43, 70.38, 79.23 at pre-operative, one month post-operative, and three months post-operative, respectively) ( $p < 0.05$  between each time point).

#### *Muscle Architecture Variables*

For the analysis determining the effects of post-surgical time on the surgical compared to the non-surgical control group, no significant group  $\times$  time interactions were found for measures of muscle architecture (Table 4.2): muscle thickness ( $F_{4,108}=1.594$ ,  $p=0.181$ ); pennation angle ( $F_{4,108}=2.097$ ,  $p=0.086$ ); fascicle length ( $F_{4,108}=1.928$ ,  $p=0.111$ ).

The angle and region of measurement were influenced by postoperative healing time. Significant angle  $\times$  region interactions were found for measures of muscle thickness ( $F_{1,55}=47.78$ ,  $p \leq 0.001$ ); pennation angle ( $F_{1,55}=5.658$ ,  $p=0.021$ ); fascicle length ( $F_{1,55}=85.204$ ,  $p \leq 0.001$ ). Simple effects produced significant differences between testing angles ( $0^\circ$ ,  $70^\circ$ ) and between testing regions (proximal, distal). Changes in muscle thickness, pennation angle, and fascicle length, at  $0^\circ$  and  $70^\circ$ , were different in proximal and distal muscle regions. Changes in muscle thickness, pennation angle, and fascicle length, at proximal and distal muscle regions, were different between  $0^\circ$  and  $70^\circ$ . At  $70^\circ$ , muscle thickness and fascicle length were greatest, while pennation angle was greatest at  $0^\circ$  (Tables 4.3, 4.4, and 4.5). Additionally, the greatest muscle thickness and fascicle length were found in the proximal muscle region, while the greatest pennation angle was found in the distal region.

Figures 4.2, 4.3, and 4.4 present a representative look at muscle thickness, pennation angle, and fascicle length across the three testing sessions for the proximal muscle region at  $70^\circ$ . The  $70^\circ$  angle data was chosen because all subjects were fully able

to position their knee into 70° of flexion during testing. There were no significant differences ( $p>0.05$ ) between groups for proximal muscle thickness, pennation angle, and fascicle length.

There were no significant differences across testing sessions in surgical knees for fascicle curvature (Figure 4.5). In attempting to quantify curvature, we used a proprietary computer program to estimate fascicle curvature at each testing session. This novel technique is a first attempt to estimate fascicle curvature. These results suggest that intramuscular pressure, which has been associated with fascicle curvature, should remain stable across time for surgical knees.

## **Discussion**

Muscle architecture measures showed no significant changes in surgical, non-surgical, or control knees over a three-month period. In surgical knees, this period involved osteoarthritis, subsequent TKA surgery, and post-operative rehabilitation. Significant differences in testing angle and muscle region were observed. Improvements in range-of-motion and Knee Society scores in our study were not paralleled by architectural changes in surgical knees.

### *Changes in Muscle Architecture over time*

The first 30 days following TKA are often the most critical for regaining strength and function (18). One of the hypotheses of this study was that increases in muscle thickness, pennation angle, and fascicle length, would occur in surgical knees at one-month post-operative, which was not supported by the results. These non-significant measures were characterized by small effect sizes (partial  $\eta^2$  of 0.05, 0.06, and 0.08 for muscle thickness, pennation angle, and fascicle length, respectively). These results were

consistent with the observed decreases in range-of-motion, but were different than the pattern seen with Knee Society scores, which improved at one-month post-operative. To provide an estimate of the degree of change in muscle architecture measures that could be considered meaningful, a coefficient of variation (COV) was calculated across testing sessions in the control group. From the pre-operative to three-month testing sessions, COV for muscle architecture variables was: muscle thickness, 1.0 mm to 1.3 mm; pennation angle, 0.2° to 1.6°; and fascicle length, 1.9 mm to 6.2 mm.

Measures of muscle architecture are directly related to force and excursion capabilities. Based solely on the present results, no changes in force and excursion would have been expected to occur over time in surgical knees (or in non-surgical and control knees). However, significant one-month post-operative decreases in force/cross sectional area and peak isometric voluntary contraction were reported in the same group of TKA subjects in a previous study (17). Potential reasons for these discrepancies include the use of the vastus lateralis as a surrogate to represent the entire quadriceps, differences in testing angle and muscle region, and instrumentation insensitivity.

Our findings are not in agreement with other reports of clinical deficiency in surgical knees one-month following TKA. Fitzgerald et al. (4) reported significant declines in physical function at this time point following unilateral TKA using the SF-36 questionnaire. Significant decreases in force (13) and volitional activation (13,22) have also been shown at the one-month post-operative testing session.

No increases in architectural measures in surgical knees were seen at three-months post-operative. This does not agree with Rossi et al. (18), who found decreased knee extensor strength in subjects undergoing bilateral TKA at one-month post-operative,

with the greatest improvement seen between 30 and 60 days post-operative. In non-surgical knees, the finding of three-month values more closely resembling pre-operative values could mean that adaptations were beginning to occur at the one-month time point but had not had sufficient time to manifest, or that the post-operative rehabilitation was not sufficient to cause immediate changes to occur.

#### *Regional Differences in Muscle Architecture*

Evaluation of muscle architecture using the vastus lateralis is typically performed at 50% of thigh length; few studies have examined these measures at different regions of the muscle (2,19,25). The present results show distinct differences in muscle thickness, pennation angle, fascicle length, and fascicle curvature as a function of muscle region. In surgical knees, muscle thickness and fascicle length showed higher values in the proximal muscle region, while pennation angle showed slightly higher values in the distal region.

These results agree with those of Scott et al. (19), who found large differences in pennation angle between the extreme proximal portions of the vastus lateralis ( $5^\circ$ ) and the extreme distal portions ( $50^\circ$ ), although no regional changes in fascicle length were found. In that study, analyses were done on a cadaver model using MRI and were made under the assumption that fascicles followed a completely straight line from origin to insertion that, in previous reports (5,6) as well as the current study, has shown to be misleading.

#### *Fascicle Curvature*

Our values for fascicle curvature (Figure 4.5) were lower than those reported for the gastrocnemius at rest (10,14). The significant correlation ( $r=0.89$ ,  $p<0.05$ ) between curvature and pennation angle agrees with that of Muramatsu (14), who found a

significant correlation between these variables using the gastrocnemius (at maximal voluntary contraction). Subjects with higher pennation angle tended to have greater curvature. Our results indicate that, even at rest where fascicle curvature is slight, it is associated with other measures of muscle architecture. As curvature significantly increases with contraction in the gastrocnemius (10,14), it can be speculated that vastus lateralis curvature would increase in the same manner.

We observed the greatest curvature in the distal muscle region, suggesting that this region could potentially develop an increase in intramuscular pressure (20) and a subsequent reduction in blood flow, as described by Miura et al. (11). Fascicles in our study curved in the same direction in both proximal and distal portions of the muscle. These results do not support the hypotheses of Otten (16), who thought that fascicles in a unipennate muscle were curved in a manner that induced bulging of the muscle (onion-like configuration), meaning that the direction of curvature would change along a muscle's length.

### *Summary and Conclusions*

Muscle architecture was not altered over time in TKA or control subjects. Architectural measures were different as a function of testing angle and muscle region. An understanding of how muscle adapts over time to different demands is critical when designing a rehabilitation program after surgery such as TKA. The use of ultrasound can provide information regarding force and excursion characteristics beyond that of a traditional clinical examination. Future studies should examine different rehabilitation protocols based on measures of muscle architecture both pre- and immediately post-

surgery. The use of ultrasound is warranted in muscle architecture studies of disuse atrophy and should be adapted to other conditions.

## **Acknowledgements**

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Table 4.1. Selected demographic, clinical, and functional characteristics of TKA subjects and control subjects at the pre-operative testing session.

	TKA (n=14)	Control (n=15)	
Age (years)	60.21 (9.1)	63.40 (10.7)	
Height (cm)	176.94 (9.2)	175.1 (9.0)	
Weight (pre-op, kg)	105.31 <sup>a</sup> (29.18)	79.33 (9.8)	
Weight change at three months (kg)	-3.88 <sup>a</sup> (7.2)	0.25 (1.8)	
	Surgical	Non-surgical	
ROM			
Extension (°)	-3.35 (4.8)	-1.33 (2.6)	0.93 (1.9)
Flexion (active, °)	115.50 (12.7)	121.27 (6.9)	134.76 (9.2)
Flexion (passive, °)	119.83 (12.8)	124.54 (6.8)	139.83 (8.6)
Knee Society Scores			
Clinical	68.36 (11.9)	76.0 (11.1)	98.67 (2.3)
Functional	56.43 (10.6)	56.67 (12.1)	100.0 (0)

Values are Mean (SD).

<sup>a</sup>Significantly different from control group (p<0.05).

Table 4.2. Repeated measures analysis of variance summary table (interaction effects involving time).

Interaction	Variable	Type III Sum of Squares	Hypothesis df	Error df	F-value	Significance	Partial Eta Squared
Time × Group	MT	0.887	4	108	1.478	0.183	0.056
	PA	53.426	4	108	1.877	0.086	0.072
	FL	19.561	4	108	2.324	0.111	0.067
Time × Angle	MT	0.214	2	54	2.145	0.120	0.075
	PA	16.661	2	54	3.138	0.103	0.081
	FL	1.821	2	54	1.316	0.258	0.049
Time × Region	MT	0.199	2	54	1.680	0.204	0.057
	PA	3.914	2	54	0.532	0.657	0.015
	FL	0.392	2	54	0.171	0.859	0.006

MT = muscle thickness

PA = pennation angle

FL = fascicle length

Table 4.3. Muscle thickness (mm) for surgical knees, non-surgical knees, and control knees across the three testing sessions.

	Pre-Operative	1 Month Post-Operative	3 Months Post-Operative
0° Proximal			
Surgical	18.2 (0.7)	17.1 (0.6)	15.8 (0.4)
Non-surgical	20.8 (0.9)	18.8 (0.9)	21.2 (0.6)
Control	19.1 (0.5)	18.6 (0.4)	18.0 (0.4)
0° Distal			
Surgical	13.8 (0.5)	12.9 (0.4)	11.6 (0.3)
Non-surgical	15.7 (0.7)	14.2 (0.6)	15.9 (0.5)
Control	13.1 (0.2)	13.2 (0.2)	12.1 (0.2)
70° Proximal			
Surgical	18.8 (0.5)	19.2 (0.6)	19.9 (0.6)
Non-surgical	21.2 (0.8)	22.4 (1.0)	23.4 (0.8)
Control	22.0 (0.5)	21.8 (0.5)	21.2 (0.4)
70° Distal			
Surgical	14.0 (0.5)	12.5 (0.3)	11.8 (0.3)
Non-surgical	15.2 (0.7)	14.7 (0.7)	15.4 (0.5)
Control	13.1 (0.3)	12.7 (0.3)	11.8 (0.2)

Values are Mean (SD).

Table 4.4. Pennation angle (degrees) for surgical knees, non-surgical knees, and control knees across the three testing sessions.

	Pre-Operative	1 Month Post-Operative	3 Months Post-Operative
0° Proximal			
Surgical	15.4 (3.5)	14.7 (3.2)	15.3 (2.7)
Non-surgical	16.6 (4.5)	14.5 (2.5)	15.7 (2.1)
Control	16.3 (3.3)	16.1 (3.2)	16.3 (2.0)
0° Distal			
Surgical	16.9 (2.3)	16.6 (3.3)	16.3 (3.1)
Non-surgical	18.5 (2.4)	16.0 (2.6)	18.1 (4.5)
Control	16.7 (3.7)	15.9 (2.9)	15.0 (2.0)
70° Proximal			
Surgical	13.2 (2.9)	13.6 (2.7)	14.1 (2.5)
Non-surgical	12.1 (1.9)	11.9 (2.6)	11.7 (1.2)
Control	13.9 (2.9)	13.3 (2.2)	13.4 (1.8)
70° Distal			
Surgical	15.3 (2.0)	16.1 (3.6)	14.4 (3.9)
Non-surgical	16.8 (2.7)	15.6 (5.4)	18.0 (5.9)
Control	13.4 (2.3)	12.7 (1.8)	12.2 (1.3)

Values are Mean (SD).

Table 4.5. Fascicle length (mm) for surgical knees, non-surgical knees, and control knees across the three testing sessions.

	Pre-Operative	1 Month Post-Operative	3 Months Post-Operative
0° Proximal			
Surgical	69.4 (2.1)	67.1 (1.7)	60.6 (1.4)
Non-surgical	71.4 (2.1)	73.3 (3.1)	78.1 (2.1)
Control	69.6 (1.2)	67.8 (1.0)	63.8 (0.7)
0° Distal			
Surgical	47.5 (1.4)	45.2 (1.2)	41.4 (0.5)
Non-surgical	48.1 (1.6)	50.9 (1.9)	52.6 (1.5)
Control	46.6 (0.6)	49.0 (0.7)	47.1 (0.6)
70° Proximal			
Surgical	83.7 (2.2)	81.7 (1.8)	82.1 (2.0)
Non-surgical	99.9 (2.6)	106.9 (4.1)	114.1 (3.1)
Control	92.9 (1.5)	95.5 (1.4)	91.6 (1.1)
70° Distal			
Surgical	52.3 (1.7)	45.6 (1.1)	47.6 (1.0)
Non-surgical	51.9 (2.3)	55.7 (2.8)	54.5 (1.5)
Control	57.1 (1.1)	57.7 (0.9)	55.8 (0.8)

Values are Mean (SD).

Figure Legends:

Figure 4.1: Typical B-mode ultrasound image of the vastus lateralis. Muscle thickness, pennation angle, and fascicle length can be clearly visualized. Also noticeable are the superficial and deep aponeuroses, the vastus intermedius, and the femur.

Figure 4.2: Top: proximal muscle thickness for surgical and non-surgical knees at 70° across testing sessions. Open circles = surgical knees, closed circles = non-surgical knees. Values are Means  $\pm$  SD. Bottom: proximal muscle thickness for surgical and control knees at 70° across testing sessions. Open circles = surgical knees, closed triangles = control knees. Values are Means  $\pm$  SD.

Figure 4.3: Top: proximal pennation angle for surgical and non-surgical knees at 70° across testing sessions. Open circles = surgical knees, closed circles = non-surgical knees. Values are Means  $\pm$  SD. Bottom: proximal pennation angle for surgical and control knees at 70° across testing sessions. Open circles = surgical knees, closed triangles = control knees. Values are Means  $\pm$  SD.

Figure 4.4: Top: proximal fascicle length for surgical and non-surgical knees at 70° across testing sessions. Open circles = surgical knees, closed circles = non-surgical knees. Values are Means  $\pm$  SD. Bottom: proximal fascicle length for surgical and control knees at 70° across testing sessions. Open circles = surgical knees, closed triangles = control knees. Values are Means  $\pm$  SD.

Figure 4.5: Fascicle curvature across testing sessions in surgical knees.

Figure 4.1

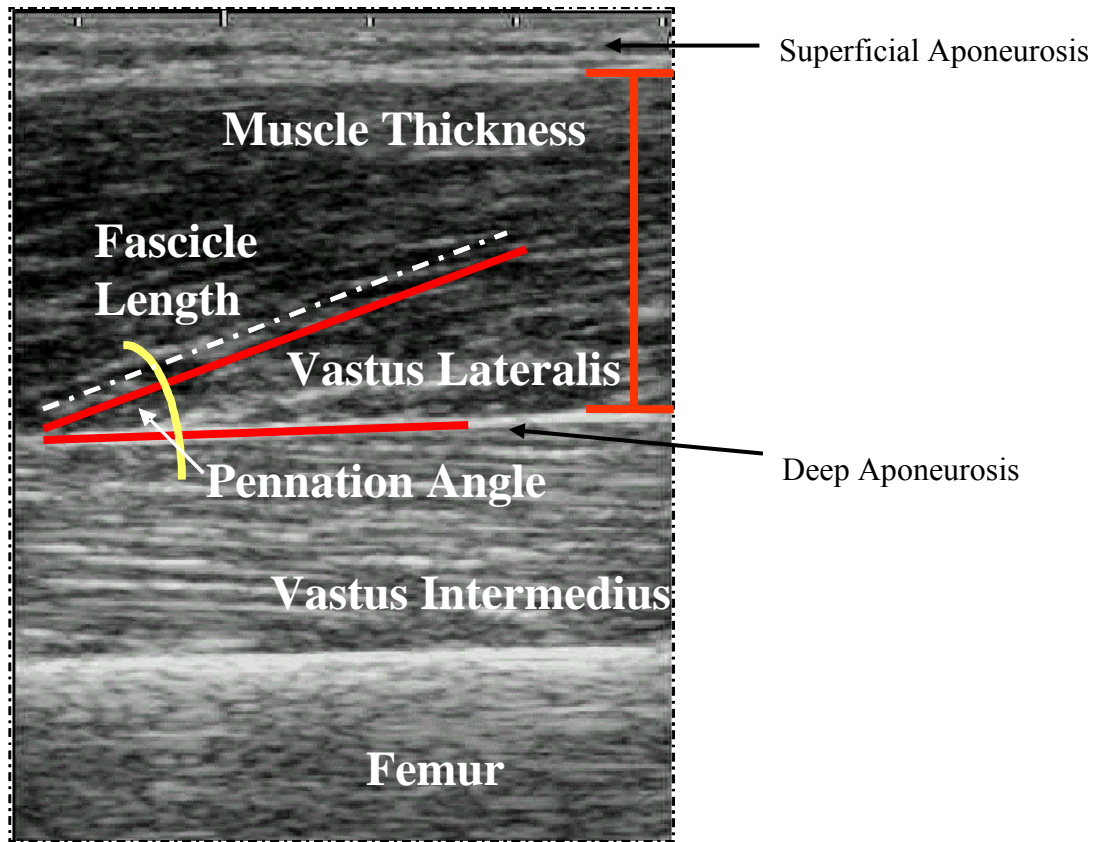
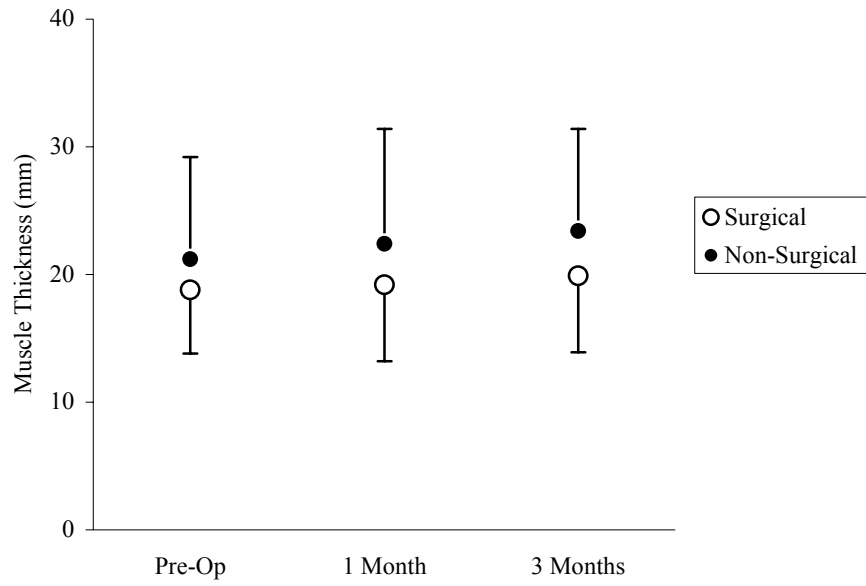


Figure 4.2

### Proximal Muscle Thickness 70° Surgical vs. Non-Surgical Knee



### Proximal Muscle Thickness 70° Surgical vs. Control Knee

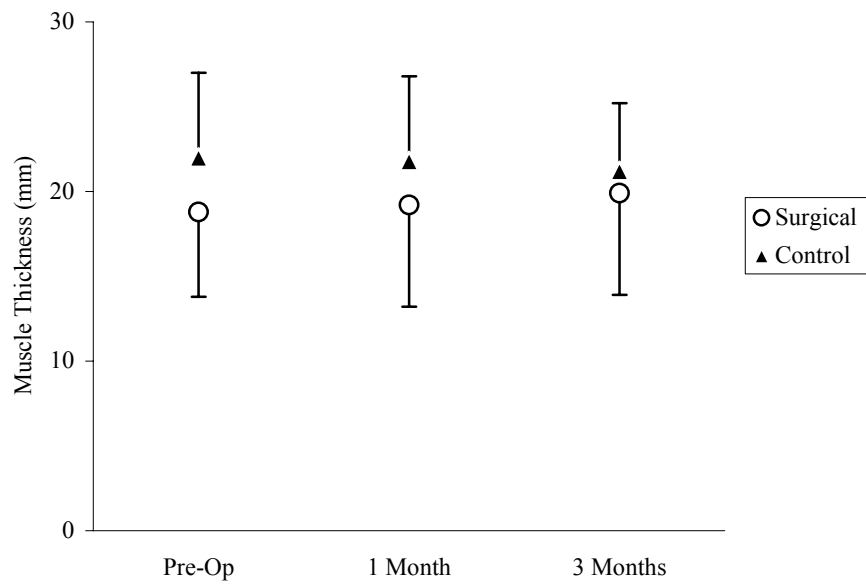
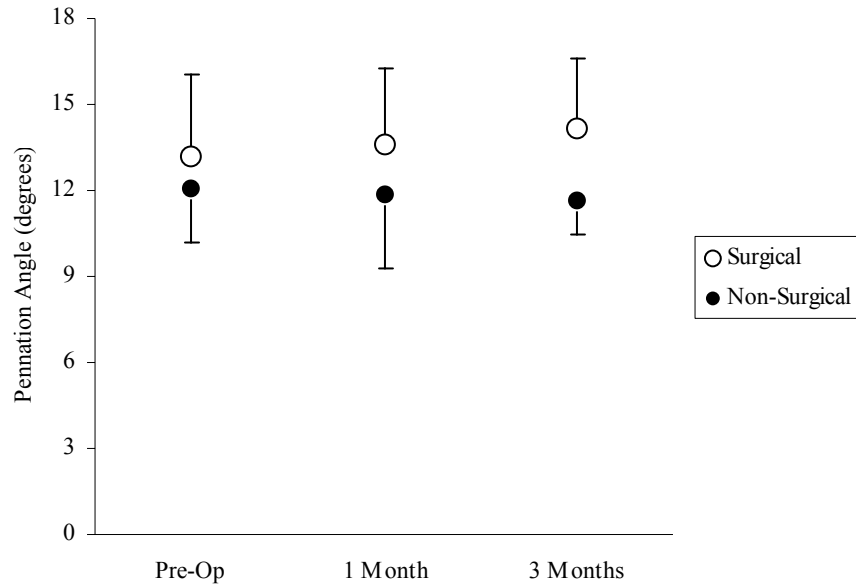


Figure 4.3

### Proximal Pennation Angle 70° Surgical vs. Non-Surgical Knee



### Proximal Pennation Angle 70° Surgical vs. Control Knee

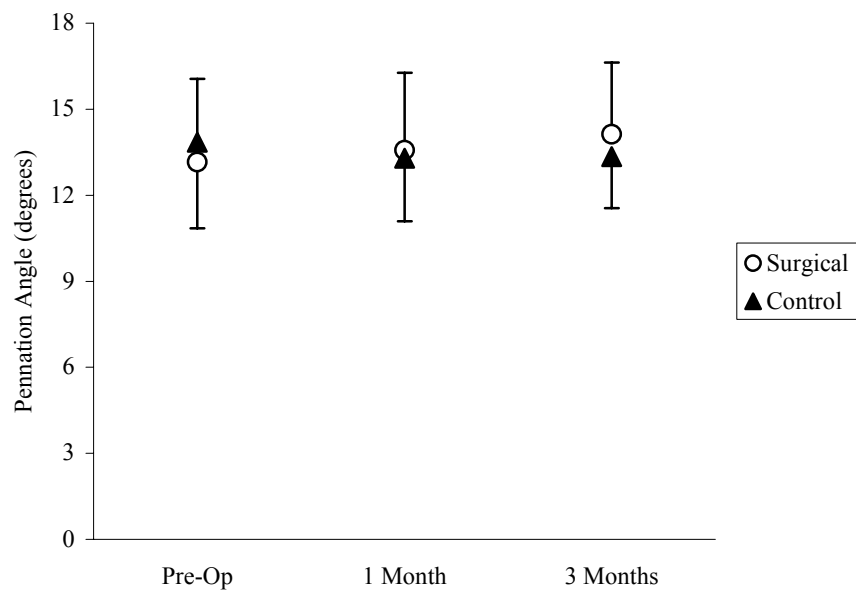
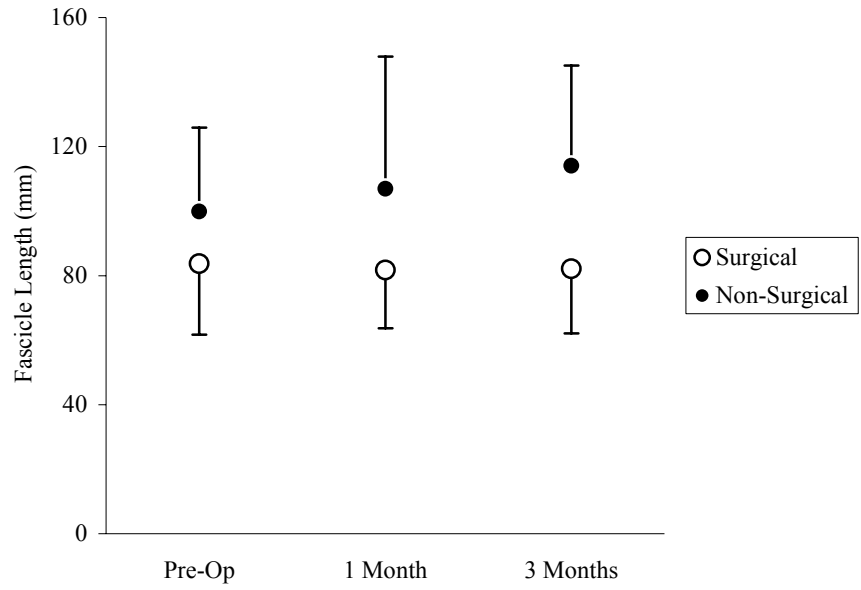


Figure 4.4

### Proximal Fascicle Length 70° Surgical vs. Non-Surgical Knee



### Proximal Fascicle Length 70° Surgical vs. Control Knee

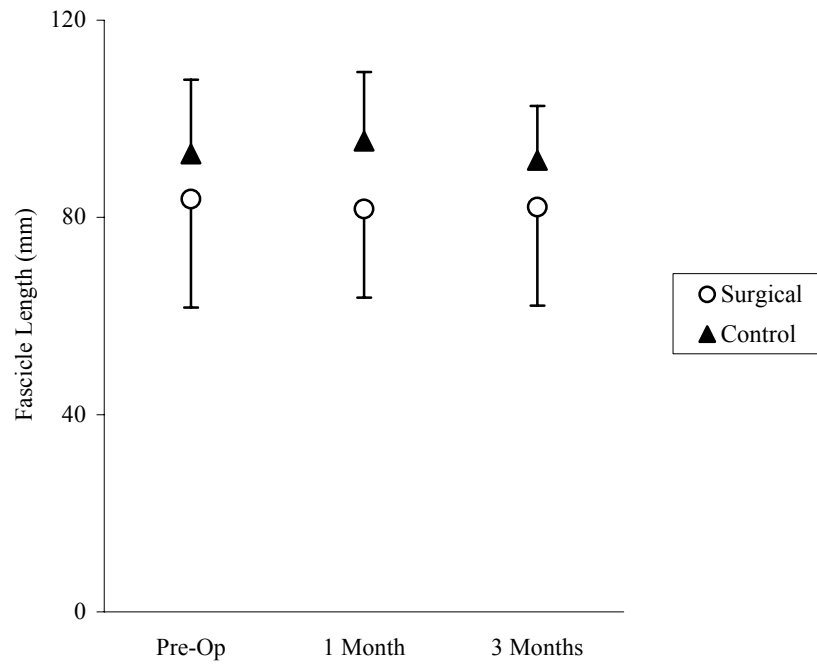
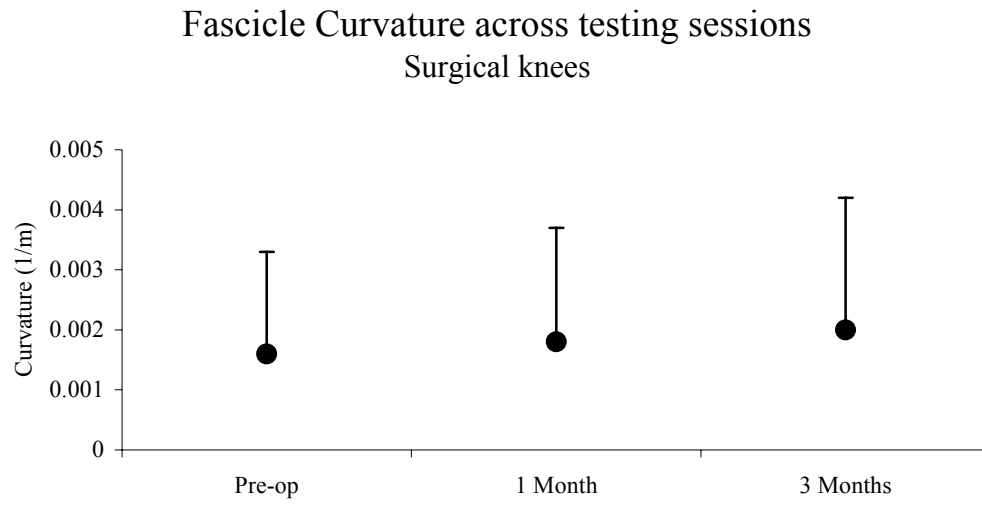


Figure 4.5



## CHAPTER V

### SUMMARY AND CONCLUSIONS

The use of B-mode ultrasound provides a valid (33,48), reliable (21,27,33), non-invasive, and inexpensive means of assessing muscle architecture in vivo. Measures of muscle thickness, pennation angle, fascicle length, and fascicle curvature can be used to explain properties of muscle function and provide additional information beyond traditional clinical examination. Although it is well known how muscle architecture adapts to hypertrophy, much less is known regarding the effects of disuse atrophy. Total knee arthroplasty is associated with deficits in strength and function following surgery that may potentially be explained by changes in muscle architecture. This study was designed to prospectively identify and characterize architecture measures in subjects undergoing TKA, both before and after surgery, compared to a group of control subjects.

Limited data have been reported with respect to muscle architecture changes following disuse. We found no significant changes in muscle thickness, pennation angle, or fascicle length in any group as a function of time. Surgical knees displayed decreases compared to non-surgical and control knees prior to surgery. The initial month following TKA has been described as the most important in terms of strength and functional recovery (59). Ours was the first study to prospectively track changes in muscle architecture in this early post-operative period following TKA. These findings do not reflect findings of decreased volitional activation (9,49,65), force (56), and strength (59)

reported in other studies following TKA. Additionally, lack of change in muscle architecture cannot be used to explain decreased force per cross sectional area and peak isometric voluntary contraction one month after surgery that were shown in the same group of TKA subjects (56).

Although fascicle curvature was evident in our study, fascicles remained nearly straight at rest. This finding agrees with other reports of fascicle curvature calculation (45,50). The significance of fascicle curvature would be manifested more in conditions of contraction, where it is known to increase and potentially affect intramuscular pressure and blood flow (62). Our proprietary computer model, introduced as an original method of calculating fascicle curvature, was based on the assumption that the fascicle shape was an arc (50) and that the radius of curvature did not change along the length of the fascicle. These assumptions have also been the basis of other attempts to calculate fascicle curvature (45,50); however, it is not known whether they were valid.

This was the first attempt in our laboratory to examine muscle architecture using B-mode ultrasound. Overall, results showed similar values to those reported in the literature. Architecture shows distinct changes as a function of both testing angle and position (21), both of which were confirmed in our study. Certain limitations played a role in our data collection. The inability to completely visualize a fascicle from deep to superficial aponeurosis led to the use of an estimation formula for calculation of fascicle length. Tester inexperience in image analysis may have been a limiting factor, although pilot data and control data revealed acceptable within-day and between-day coefficient of variation.

The use of ultrasound can provide additional information beyond that of a traditional clinical examination. In our study, lack of change in measures of muscle thickness, pennation angle, and fascicle length, and regional changes in these variables, were not reflected by clinical results (improvements in range-of-motion, Knee Society scores). Thus, the method can serve as a useful tool in rehabilitation to individually identify muscle regions whose architectural characteristics may not be optimized. Specific types of training programs have been shown to produce improvements in muscle architecture (1,10,58,60), which can potentially be applied to rehabilitation. Future studies should address the role of different rehabilitation protocols on muscle architecture, as well as applying ultrasound techniques to other conditions of disuse atrophy.

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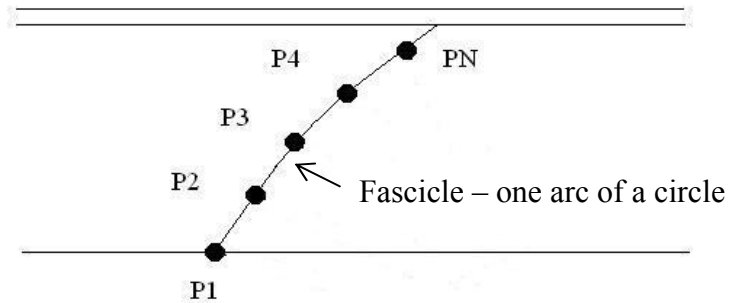
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APPENDIX A  
CALCULATION OF FASCICLE CURVATURE

- Four points were manually digitized on the fascicle (Figure A1, points 1-4 (P1-P4) using the ultrasound image. It was assumed that the fascicle shape was an arc (50); thus, the radius of the arc did not change along the length of the fascicle.

Figure A1



- Chords were generated based on all possible combinations of the digitized points on the fascicle (from P<sub>1</sub> to P<sub>N</sub>, Figure A2). For each chord:
  - Slope and y-intercept were calculated.
  - A perpendicular line bisecting each chord was generated.
- The common intersection points of the perpendicular lines were derived by solving simultaneous equations and then averaged to produce the center point of the arc
  - The radius of the arc was determined by determining the length between P<sub>1</sub> and the center point of the arc.
- The angle of curvature ( $1/r$ ) was calculated.

Figure A2

