[Imaging]

Interaction of Gender and Body Composition on Rectus Femoris Morphology as Measured With Musculoskeletal Ultrasound Imaging

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Background: Quadriceps function is an important measure in patients recovering postoperatively. Traditionally, strength measures that require high levels of resistance are contraindicated during the early postoperative phase. Thus it may be helpful to evaluate the utilization of other tools, such as ultrasound imaging, that allow for assessment during a position of low resistance.

Hypothesis: The rectus femoris cross-sectional area (CSA) is affected by sex and body composition in healthy subjects.

Study Design: Cross-sectional study.

Level of Evidence: Level 4.

Methods: Thirty-two healthy subjects (16 women, 16 men), selected from a previously larger study, were chosen for analysis. All subjects underwent a maximal volitional isometric contraction protocol from 0° to 90° of knee motion controlled by an isokinetic dynamometer. In the contracted and resting positions, the rectus femoris CSA was measured at each angle using ultrasound imaging. The contractile index (contracted − resting CSA) was calculated at each position. Subjects were separated into 1 of 4 groups based on sex and fat percentage (low or high). These data were analyzed using mixed-factor analysis of variance (group × angle) for each variable, with a critical α level of 0.05.

Results: A significant interaction was noted for the CSA of the rectus femoris at rest ($P < 0.03$) and during contraction ($P < 0.02$). For both variables, all groups performed similarly, with the exception of women with high body fat percentage. No statistically significant interaction existed for the contractile index; however, a main effect for angle ($P < 0.01$) was observed.

Conclusion: Rectus femoris CSA appears to depend on sex as well as the body composition of individuals.

Clinical Relevance: Traditional subjective assessment measures of quadriceps strength and function have low reliability and functional validity. With the improved feasibility of ultrasound imaging in the clinical setting, quadriceps size may be more accurately measured during the early postoperative stages.

Keywords: body composition; cross-sectional area; gender; muscle activation; ultrasound imaging

Quadriceps weakness is considered a hallmark of knee dysfunction.[1] The importance of quadriceps strength has been noted for a variety of pathologies, such as osteoarthritis and anterior cruciate ligament reconstruction, and after total knee replacement.[1,8,24] Preoperative quadriceps muscle weakness has a significant negative effect on the long-term functional outcome after knee surgeries.[8,24] Furthermore, quadriceps weakness may initiate and contribute to the damage

Table 1. Descriptive statistics (mean ± SD)

Variable	Men		Women	
	Low % Body Fat	High % Body Fat	Low % Body Fat	High % Body Fat
Age, y	26.3 ± 3.6	28.8 ± 3.4	26.4 ± 2.4	26.1 ± 3.3
Height, m	1.80 ± 0.05	1.79 ± 0.10	1.66 ± 0.06	1.61 ± 0.08
Mass, kg	75.3 ± 7.6	85.2 ± 18.1	58.2 ± 3.6	65.7 ± 9.1
Body mass index, kg/m^2	23.3 ± 2.6	26.4 ± 4.4	21.3 ± 1.8	24.0 ± 3.4
Percentage body fat	8.6 ± 1.5	24.8 ± 5.8	20.1 ± 2.7	30.7 ± 2.7

of articular cartilage and other tissues susceptible to osteoarthritis.[23] Thus, quadriceps strengthening is a key focus during rehabilitation to decrease pain and increase function.[23] In the clinical setting, quadriceps strength is measured subjectively by utilization of manual muscle testing, 1-repetition maximum knee extension, and straight-leg raise; however, these measures tend to have low reliability and functional validity.[11] Furthermore, most of these measures are contraindicated during early postoperative rehabilitation due to surgical precautions and/or postoperative pain. Thus, novel measures to reliably assess the quadriceps in acceptable ways are necessary to improve clinician understanding of patient outcomes.

One way to assess isolated muscle performance in a resistance-free environment is by examining the size of a muscle. Magnetic resonance imaging currently serves as the gold standard to assess architectural characteristics of muscle.[26] However, ultrasound imaging (USI) is less expensive and a more readily available option.[2] In addition, USI is a valid and reliable tool to measure components of muscle morphology and morphometry.[26] When considering the use of USI to measure muscle thickness, width, length, and cross-sectional area (CSA), studies have shown good agreement (>0.80) between measures to assess muscle size. Because of the architectural characteristics of the rectus femoris, CSA is easily measured using USI, as the entire perimeter of the rectus can be captured in the field of view.[26] Blazevich et al[3] determined that the superficial quadriceps muscles act together via the common extensor tendon, which is suggestive of similarity in function. Therefore, examining the rectus femoris utilizing USI provides a global view of the quadriceps function as a whole. Furthermore, assessing both the size of the rectus femoris and the contraction of the extensor mechanism may give clinicians an added ability to identify limitations in quadriceps performance. Previous work by Delaney et al[7] has examined the relationship between rectus morphology, force generation, and muscle activation. During maximal knee extensor contraction, there was a 10% increase in the depth with a concomitant 25% decrease in width of the rectus femoris. This finding would suggest that rectus femoris CSA, as a whole, is inversely related to force production and muscle activation. During quadriceps contraction, the relatively small rectus femoris was encroached by the surrounding larger musculature (vastus intermedius, vastus lateralis, and vastu medialis), which led to this inverse relationship.[3,27] Myers et al[19] determined that rectus femoris CSA is also affected by and directly related to knee flexion range of motion in the relaxed and the contracted states.

Muscle contraction can be affected by a variety of internal factors, including, but not limited to, swelling, pain, weakness, joint damage, and neurologic inhibition.[10,14,17,20,21] Quadriceps weakness is considered a hallmark of knee dysfunction, thus it is imperative to explore all factors that can affect voluntary activation of the rectus.[1] Decreased activation affects full and rapid recovery of the quadriceps femoris muscle force following surgical and nonsurgical disorders.[15,18,21] While one would typically associate an increase in CSA with increased force, knee flexion range of motion and the encroaching musculature during contraction affects CSA of the rectus femoris.[3,19,27] Thus, to initially understand this relationship, healthy subjects were analyzed in an isolated manner. To date there are no studies that explore the effect of inherent factors such as body composition and sex on CSA. As a result, the aim of this study was to determine whether relationships exist between rectus femoris CSA, sex, and body composition in healthy subjects. Specifically, the purpose of this study was to determine whether there is an interaction of sex and body composition on CSA measurements of the rectus femoris using USI across knee range of motion.

METHODS

Participants

Thirty-two healthy subjects, selected from a previous larger study,[19] were chosen for analysis. These subjects represented the participants with the 8 highest and 8 lowest percentages of body fat within a larger sample, removing a central group of individuals to improve heterogeneity of the groups (Table 1). Individuals for the initial study were recruited through email, flyers, and word of mouth. Subjects were excluded if they had a past history of lower extremity injury, surgery, or neurologic/

Figure 1. Ultrasound image of a relaxed quadriceps including rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), and vastus intermedius (VI).
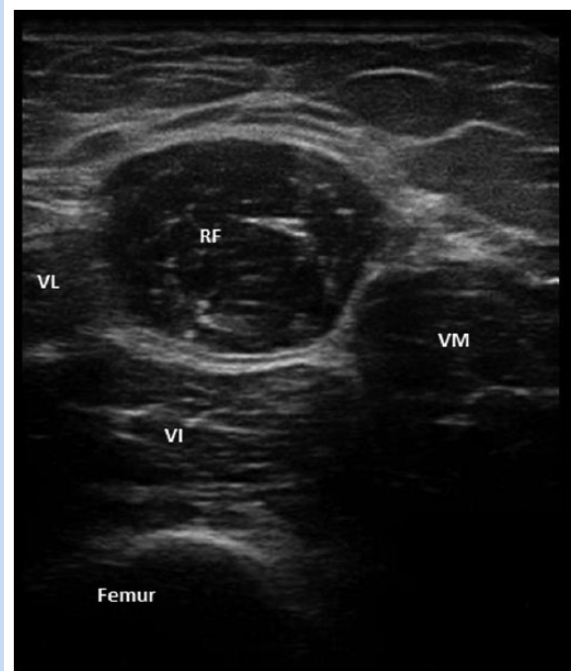

Figure 2. Ultrasound image of a maximally contracted quadriceps including rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), and vastus intermedius (VI).

musculoskeletal dysfunction that limited activities of daily living. All subjects signed a medical consent form. The study protocol was approved by the institutional review board at the medical center where the study was conducted.

Physical Assessment

Height was measured using a double beam height and weight scale (Health-O-Meter, Inc). Each subject was then prepared for body composition testing using the Bod Pod Body Composition tracking system (Life Measurement, Inc), as outlined in the user manual.[4] Body composition analysis was calculated with estimated lung volume. The protocol requires each subject to don a spandex swimsuit, remove all jewelry, and wear a swim cap for uniformity. Furthermore, all subjects fasted for 4 hours and refrained from exercise 1 hour prior to testing to improve the validity of the body composition measurement.

Isometric Testing

Directly after body composition analysis, subjects performed 5 minutes of stationary cycling at a self-selected, comfortable speed. Directly after the warm-up, isometric testing was performed using an isokinetic dynamometer (Humac/Norm TM Testing and Rehabilitation System, Model 770 Computer Sports Medicine Inc). The machine was operated per the user manual protocol for seated isometric knee extension at 90°, 60°, 30°, and 0° of knee flexion.[13] The 0° (neutral) measurement was determined using passive range of motion and clinician observation. The subsequent test angles were automatically

determined by the preset Cybex program, and testing was performed at 90°, 60°, 30°, and 0° of knee flexion, respectively. At each angle, 3 images of the rectus femoris were obtained both at rest and during contraction, for a total of 6 images. The mean of the 3 trials was used for data analysis. During the contraction trials, each subject was instructed to apply a maximum volitional isometric contraction (MVIC) of the knee extensors for 5 seconds. One practice contraction was allowed prior to the collection of 3 recorded trials. A 10-second rest was allotted between each trial, and a 20-second rest was allotted between each angle.

Ultrasound Imaging

A portable ultrasound machine (2009 MyLab25 Gold Portable Ultrasound System; Esaote North America) was used to measure rectus femoris CSA during both the relaxed and the contracted phases of isometric testing. All ultrasound measurements were performed by the same experienced clinician. Reliability of the measurements was established during baseline testing performed on different days. The ultrasound transducer was placed 15 cm proximal to the superior pole of the patella[5] and maintained in a perpendicular orientation to the longitudinal axis of the RF muscle. This location was marked with indelible ink and was used for all measurements. Images of both the relaxed (Figure 1) and the isometrically contracted (Figure 2) rectus femoris were captured for 5 trials at 90°, 60°, 30°, and 0° of knee flexion.
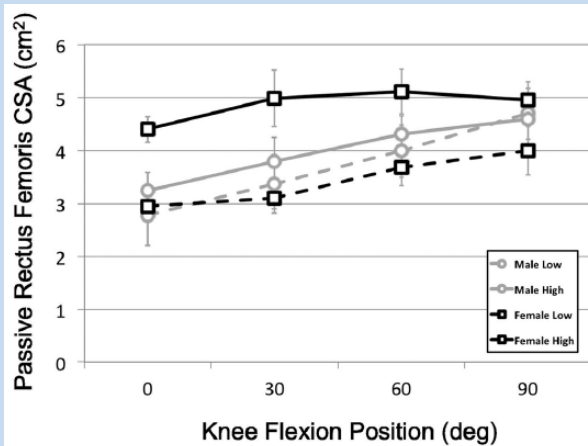
Figure 3. Cross-sectional area of the rectus femoris when measured at rest across multiple angles of knee flexion.
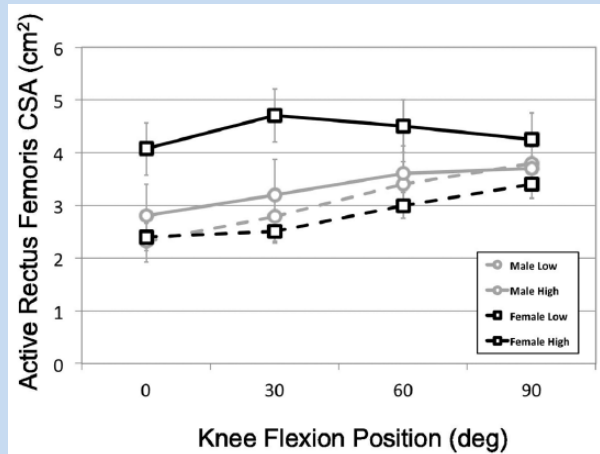

Figure 4. Cross-sectional area of the rectus femoris when measured during maximal volitional activation across multiple angles of knee flexion.

Statistical Methods

The variables of interest for this study were the CSA of the rectus femoris at multiple angles of knee flexion both at rest and undergoing MVIC; the contractile index, which was calculated as the difference between the CSA during rest and during the MVIC; and body composition. Although not statistically significant in the prior study,[19] the independent factor of sex was also considered during the analysis. Consideration of both variables, sex and body composition, may yield more significant results when men and women are categorized as having either high or low body fat percentage. Mixed-factor analyses of variance (group × angle) were utilized to examine the differences across the angles of knee flexion for the 3 different conditions (at rest, MVIC, and contractile index) and the 4 different groups (male/high [MH], female/high [FH], male/low [ML], female/low [FL]). Statistical significance was identified at $P < 0.05$ for interactions and main effects. Post hoc analyses for significant interactions and main effects were completed using the Tukey honestly significant difference model.

RESULTS

No differences existed in age across the groups (see Table 1). The male groups were taller and had a greater mass than the female groups; however the only difference in body mass index was between the FL and MH groups. Statistical differences also existed for all groups for body fat percentage with the exception of no statistical difference existing between the FL and MH group.

The CSA of the rectus femoris at rest demonstrated an upward trend for both male groups and the female group with low body fat percentage as the knee flexion angle increased. The female group with high body fat percentage had an increase in CSA from 0° to 30°, and the CSA remained relatively constant from 30° to 90°. A statistically significant interaction ($P < 0.03$) was observed for this relationship (Figure 3).

During maximal contraction, the rectus femoris CSA had a smaller value than at rest. The CSAs for both male groups and the female group with low body fat percentage increased as knee flexion angles increased, mirroring the trend observed during the relaxed condition. The female group with higher body fat percentages had an increased CSA from 0° to 30° of knee flexion. As knee flexion increased past 30°, the CSA acted inversely and gradually decreased from 30° to 90°. A statistically significant interaction ($P < 0.02$) was observed for this relationship (Figure 4).

The difference between the values of the CSAs of the rectus femoris at rest and at maximal contraction was identified as the contractile index. There was no statistically significant interaction, but a main effect for angle was observed ($P < 0.01$). The contractile index was observed to decrease across range of motion for all the groups. Both male groups and the female group with low body fat percentage maintained a consistent decrease in their contractile index as knee flexion angle increased. The female group with high body fat percentage had minimal change in contractile index from 0° to 30° of knee flexion, but then showed a sharp decrease from 30° to 60° of knee flexion. From 60° to 90° of knee flexion, the female group with high body fat percentage had similar contractile index to the other 3 groups (Figure 5).

DISCUSSION

Rectus femoris morphology and contractility appear to depend on sex as well as the body composition of an individual. Measurements of the rectus femoris CSA during the relaxed state increased as knee flexion range of motion increased for both male groups and the female group with low body fat percentage. In contrast, the female group with higher body fat
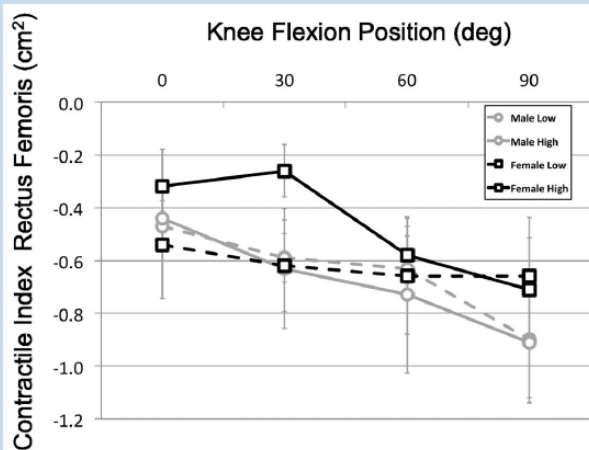
Figure 5. Change in cross-sectional area of the rectus femoris between resting and a state of maximal volitional contraction.

percentages maintained a more constant CSA during rest at larger angles. During contraction, only the high body fat percentage female group had greater CSA from 0° to 30°, which consistently decreased as the angles increased. The female group with increased body fat percentage in this study also demonstrated a smaller contractile index value than the other 3 groups. Although not statistically significant, this may indicate decreased quadriceps activation, particularly between 0° and 30° of knee flexion, which is of functional relevance to the lower extremity.

The findings from this study readily translate into clinical relevance since quadriceps activation during 0° to 30° of knee flexion is an important factor in stabilizing the lower extremity during the stance phase of gait and during sporting activities such as jump landings. Decreased quadriceps function during the stance phase of gait, whether inherent or a functional adaptation due to injury such as anterior cruciate ligament deficiency (ie, quadriceps avoidance gait pattern), may lead to associated knee injuries or posttraumatic osteoarthritis.[25] Assessing both the size of the RF and the quality of the extensor mechanism contraction under dynamic musculoskeletal ultrasound imaging during rehabilitation may identify limitations in quadriceps performance. Early intervention in the form of corrective therapeutic exercise progression to address these deficits may lead to better long-term outcomes.

Long-term knee health depends on the protection of joint surfaces from impact and torsional loads. Knee stability requires muscle strength, recruitment, and timing. Contraction of muscles can help with this protection while decreased neuromuscular control during joint loading can increase the risk of joint damage.[5] The female group in this study with higher body fat percentages had larger rectus femoris CSA values both at rest and during contraction than comparison groups. Subjects who

demonstrate greater muscle mass do not necessarily generate more force than those with less muscle mass.[23] In the larger study, as knee flexion increased, female participants became less able to reduce the CSA of the rectus femoris in comparison with the male participants.[19] This difference appears to be somewhat attributed to sex-specific factors such as percentage fat mass, which is directly associated with muscle activation.[16] There is a significant correlation between lean body mass and strength, with the conclusion that adipose tissue cannot generate force.[16] This may provide a rationale as to why the female participants with higher fat mass demonstrated an inability to continuously reduce the CSA of the rectus femoris in a similar manner. Women who have a higher body fat percentage and demonstrate a decreased ability to contract the knee extensors may be at an increased risk of joint degeneration. In fact, individuals with increased body mass are 1.7 times more likely to develop knee osteoarthritis.[12] Those who suffer a knee injury are 5 times more likely to develop knee osteoarthritis—a much greater risk than weight alone.[12]

Limitations existed in the current study that should be discussed. One was the location of the ultrasound image. While this location was validated in prior studies,[6,8,9,22] 15 cm proximal to the superior pole of the patella may not measure the same portion of the rectus femoris for subjects of variant heights. Utilizing a body relative measure, such as 50% distance of femur length, is also a reliable method to measure the rectus femoris CSA[9] and may be more clinically relevant when comparing muscle size across groups with inherently different body morphology. Another limitation of this study was a lack of randomization of the order of the isometric contraction, which could have influenced fatigue. An additional limitation was the inability to consider thigh circumference as a variable of interest. The collection of this additional variable would have allowed for normalization of the rectus femoris CSA to the thigh circumference. This may have explained some of the relationships.

Additionally, obtaining images of only the rectus femoris to make generalizations regarding the strength and function of the extensor mechanism as a whole is limited in scope. Determining protocols with improved technology to image the quadriceps as a whole may be helpful in relating size to function. If force output during the isometric contractions was collected, some of the variance of the results may have been explained; however, this was beyond the scope of the current protocol. Finally, the current study results are based on a healthy cohort of subjects. More clinically relevant conclusions may be drawn from subjects with musculoskeletal dysfunction.

CONCLUSION

Rectus femoris size and contractility appear to differ between sexes and body compositions. Specifically, women with elevated body fat percentage appear to have more difficulty contracting the knee extensor mechanism, as evidenced by the smaller contractile index value measured in this study.

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