Spor Hekimliği Dergisi, 57(1):21-30; 2022
Turkish Journal of Sports Medicine
Turk J Sports Med DOI:10.47447/tjsm.0585

Research Article / Araştırma Makalesi

Rectus femoris muscle thickness and cross-sectional area on ultrasonography may predict isometric and isokinetic knee extension strength: A cross-sectional study

Rektus femoris kas kalınlığı ve çapraz kesit alanının ultrasonografik ölçümü dizin izometrik ve izokinetik ekstansiyon kuvvetini öngörebilir: Kesitsel bir çalışma

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ABSTRACT

Objective: To examine the relationship between knee extensor strength and quadriceps muscle architecture evaluated with ultrasonography during relaxed and contracted situations.

Materials and Methods: A total of 40 healthy participants (age range 18-40), doing sports at a recreational level were included. Pennation angle, muscle thickness, and cross-sectional area of the vastus medialis, vastus lateralis, and rectus femoris muscles were measured firstly during rest while participants are sitting on an isokinetic dynamometer with their knees at 0° and 60° of flexion. Thereafter, ultrasound evaluations were performed during maximal isometric contraction at 60° knee flexion and maximal isokinetic contraction at 30°/sec and 60°/sec speeds. The architectural parameters were correlated with peak isometric (measured at 60° knee flexion) and isokinetic (measured at 30°/sec and 60°/sec angular velocities) torque values.

Results: Pennation angle ($p<0.001$), muscle thickness ($p<0.001$) and muscle cross-sectional area ($p<0.001$) of the vastus medialis muscle during rest, and isometric and isokinetic maximal contractions were higher than the vastus lateralis and rectus femoris muscles. Pennation angle, muscle thickness and muscle cross-sectional area parameters measured during rest, and isometric and isokinetic maximal contractions in the vastus medialis (r=0.39-0.64, p<0.05-0.01) and vastus lateralis (r=0.36-0.68, p<0.05-0.01) showed weak to moderate correlations with isometric and isokinetic peak torque. In rectus femoris muscle, on the other hand, except the weak correlation in pennation angle (r=0.35-0.49, p<0.05-0.01), muscle thickness (r=0.74-0.80, $p<0.001$) and cross-sectional area (r=0.71-0.80, $p<0.001$) had a moderate to strong correlation with isometric and isokinetic strength. Stepwise regression analysis indicated that rectus femoris cross-sectional area measured during knee relaxed at 60° flexion (R2=0.532-0.610) and rectus femoris muscle thickness measured during isometric and isokinetic contraction modes (R2=0.538-0.600) were decisive to predict the isometric and isokinetic strength of the quadriceps muscle.

Conclusion: Contrary to pennation angle, muscle thickness and cross-sectional area of the rectus femoris measured during relaxed and contracted conditions may be determinative in predicting isometric and isokinetic strength.

Keywords: *Ultrasonography, quadriceps architecture, quadriceps static strength, quadriceps dynamic strength*

ÖZ

Amaç: Diz ekstansiyon kuvveti ile ultrasonografi ile değerlendirilen kuadriseps kas mimarisi arasındaki ilişkiyi değerlendirmektir.

Gereç ve Yöntemler : Çalışmaya 18-40 yaşları arasında, sağlıklı ve rekreasyonel düzeyde spor yapan toplam 40 katılımcı dahil edilmiştir. Vastus medialis, vastus lateralis ve rektus femoris kaslarının diz 0° ve 60° fleksiyonda dinlenimde, 60° fleksiyonda maksimal izometrik kasılmada, 30° ve 60°/sn açısal hızlardaki maksimal izokinetik kasılmalardaki mimari özellikleri ölçülmüştür.

Bulgular: Dinlenim ile izometrik ve izokinetik maksimal kasılmalar sırasında vastus medialis pennasyon açısı ($p<0.001$), kas kalınlığı ($p<0.001$) ve çapraz kesit alanı ($p<0.001$) vastus lateralis ve rektus femoristen daha büyük çıkmıştır. İstirahat durumuna göre izometrik ve izokinetik maksimal kasılmalar arasında pennasyon açısı (p<0.05-0.001) ve kas kalınlığı ($p<0.001$) artışları en fazla rektus femoriste olmuştur. Vastus medialis (r=.39-64, p<0.05-0.01) ve vastus lateralisin (r=.36-68, p<0.05-0.01) istirahat ve maksimal kasılmalar sırasında ölçülen pennasyon açısı, kas kalınlığı ve çapraz kesit alanı izometrik ve izokinetik kuvvetlerle zayıf-orta korelasyon gösterirken, rektus femorisin pennasyon açısı (r=.35-49, p<0.05-0.01) izometrik ve izokinetik kuvvetlerle zayıf, kas kalınlığı (r=.74-80, $p<0.001$) ve çapraz kesit alanı (r=.71-80, $p<0.001$) ise orta-güçlü bir korelasyona sahip olmuştur. Her üç kasa ait pennasyon açısı, kas kalınlığı ve çapraz kesit alanı verilerine ait yüzdesel değişimlerle kas kuvvetleri arasında bir ilişki saptanmamıştır ($p>0.05$). Adımsal regresyon analizine göre izometrik, 30°/sn ve 60°/sn açısal hızdaki izokinetik kuvveti ön görmede en fazla 60° diz fleksiyon açısında rektus femoris kasında ölçülen çapraz kesit alanı (R2=0.532-0.610), ikinci sırada da kasılmalar sırasında yine rektus femoris kasında ölçülen kas kalınlığı (R2=0.538-0.600) belirleyici olmuştur.

Sonuç: Pennasyon açısının aksine istirahat ve kasılmalar sırasında ölçülen rektus femoris kas kalınlığı ve çapraz kesit alanı izometrik ve izokinetik kuvveti tahmin etmede belirleyici olabilir.

Anahtar Sözcükler: *Ultrasonografi, kuadriseps mimarisi, kuadriseps statik kuvveti, kuadriseps dinamik kuvvetin*

Received / Geliş: 02.07.2021 · **Accepted / Kabul:** 16.08.2021 · **Published / Yayın Tarihi:** 11.12.2021

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Cite this article as: Sekir U, Yalaki UC, Akova B. Rectus femoris muscle thickness and cross-sectional area on ultrasonography may predict isometric and isokinetic knee extension strength: A cross-sectional study. *Turk J Sports Med.* 2022;57(1):21-30; http://doi.org/10.47447/tjsm.0585

INTRODUCTION

Skeletal muscle strength is associated with muscle mass and architecture (1, 2). Cross-sectional area and pennation angle of the muscles are among the parameters used to evaluate muscle mass and architecture (3, 4). It has also been shown that the strength-velocity relationship in skeletal muscles is closely related to the parallel structure represented by the cross-sectional area of the sarcomeres and the longitudinal structure represented by the fascicular length (2). The increase in muscle size, which is one of the indicators of muscle strengthening, affects the muscle structure by increasing the pennation angle of the muscle fascicles (3, 4). The larger the pennation angle, the more contractible material is collected in a particular volume, and the muscle capacity to produce strength increases (5).

Isokinetic dynamometers are preferred mostly to evaluate muscle strength (6). However, its use in patients with injuries, pain, muscle diseases and in intensive care units for evaluating muscle strength and functional capacity is limited, because of the difficulties to obtain maximum strength in these patients (7-9).

Muscle thickness, cross-sectional area, and pennation angle contribute to strength-generating capacity of the muscle and can be easily assessed by ultrasonography (US), a non-invasive, less costly and more accessible method (10-12). Furthermore, qualitative and quantitative measurements about these parameters can be accomplished with US (5, 11, 13). The most significant disadvantage of the ultrasound imaging method is the limited image size, because it does not allow a direct measurement of the cross-sectional area of large muscles.

In order to give physiological information about muscle function, quadriceps muscle structure evaluations with ultrasonography are usually performed during rest at 0-20° knee flexion and are associated with isometric strength measured at 90° knee flexion (3, 7, 14-17). These studies showed that vastus intermedius muscle thickness and pennation angle (7), quadriceps muscle thickness (17), and quadriceps muscle pennation angle (14) were associated with the maximal isometric strength of the quadriceps muscle. Muscle structure represents a wide range of change during contraction and the fibrillary properties of the muscle structure are directly related to the changes in the muscle structure during contraction (2). Although the muscle structure properties in resting state are considered to be an essential physiological determinant for evaluation of muscle function, the changes in muscle structure and morphology during contraction might provide more information about muscle strength and functions. Besides, strength generation of quadriceps muscle occurs at 60° knee flexion (18). It would be more meaningful to evaluate the architectural structure of the quadriceps muscle at 60° knee flexion and its capacity to produce strength. Only Massey et al. examined the quadriceps muscle architecture at 60° knee flexion both at rest and at maximal isometric contraction and showed that only the cross-sectional area is associated with the maximal isometric quadriceps strength (8). Apart from static contractions, examination of the muscle structure with ultrasonography during dynamic contractions may provide information about strength production. There are no studies linking muscle strength with the change in muscle structure during dynamic contraction.

Therefore, the purpose of this study is to examine the architecture of the quadriceps muscle during rest and maximal contractions (static and dynamic) and to see whether the properties in muscle architecture (pennation angle, muscle thickness, and cross-sectional area) during isometric and isokinetic contraction can be a predictive marker about maximal isometric and isokinetic strength.

MATERIALS AND METHODS

Study population and data collection

According to power analysis based on the results of previous studies, minimum of 18 participants in each gender should be included in the study to detect a mean difference of 10% and a standard deviation corresponding to 15% between the variables that would have at least 80% power and $p<0.05$ significance level (PASS13 Power Analysis and Sample Size Software; NCSS, LLC, Kaysville, UT). Accordingly, a total of 40 healthy participants, between the ages of 18-40, consisting of men (n=20; average age 23.9±1.6 years; average height 176.3±4.6 cm; average body weight 75.6±9.3 kg; average fat percentage 12.6%±6.0) and women (n=20; mean age 23.2±1.5 years; average height 164.8±7.3 cm; average body weight 55.2±6.5 kg; average fat percentage 19.2±4.9%) performing sports activities at a recreational level were included. Participants who had a history of injury to the lower extremity in less than 6 months from the start of the tests; who had existing injuries related to the waist, hip, knee or ankle; who had suffering from pain, swelling or functional impairment in these joints, and who had a significant limitation in range of motion of the hip, knee, and ankle were excluded from the study. In addition, neuromuscular disease, cognitive impairment, malignancy, pregnancy, and using any medication that would affect muscle strength were accepted as exclusion criteria. Furthermore, it was planned to exclude participants who developed pain, swelling, or limitation of movement in their knees and ankles due to any reason during the study. Tests were performed on the knee joints of the dominant extremity of the participants. The leg which the participants normally kick a ball was determined to be dominant. Measurements were taken from the 18 right- and 2 left-dominant legs in males and 16 right- and 4 left-dominant legs in women. Participants were given detailed information about the study and signed the "Informed Volunteer Consent Form" which includes preliminary information about the test procedure and possible risks. This form was approved by the University's Medical Research Ethical Committee for Protection of Human Participants (Approval Number 2018-4/37).

Study design

The tests were carried out at the same time period (between 14:00 and 15:00) to avoid possible effects of the circadian rhythm on the results. All participants were warned not to use alcohol or medication on the test days and to avoid strenuous physical activity. Height, weight, and fat percentage of the participants were measured, and their dominant sides were determined before the tests. To be familiar with the ultrasonographic measurements and the isokinetic dynamometer, participants were let to do isometric and isokinetic strength trials on the isokinetic dynamometer while ultrasonography of the quadriceps muscle was performed simultaneously.

All measurements were completed within one day. The ultrasonography of the quadriceps muscle (vastus medialis, vastus lateralis and rectus femoris) was performed during a) rest at 0° and 60° knee flexion, b) isometric knee extension at 60° of knee flexion, and c) isokinetic knee extension at angular velocities of 30°/sec and 60°/sec.

Strength measurements

The isokinetic dynamometer device (CSMI Humac Norm, USA) was calibrated before each test. The dynamometer was adjusted according to the knee joint as indicated by the manufacturer. The length of the dynamometer was adapted according to the leg length of each participant while the participants were sitting on the device to do flexion-extension to the knee joint. The participants were motivated with verbal commands to produce their maximal strengths.

Maximal isometric knee extension test was carried out at 60° knee flexion with six repetitions, each repetition lasting for 5 seconds. The isokinetic concentric contraction was performed in the direction of knee flexion to extension (knee joint angle between 90° to 0°) at angular velocities of 30°/sec and 60°/sec. Each test velocity consisted of 6 repetitions. A minimum of 60 seconds rest was applied between repetitions and testing modes to prevent muscle fatigue. The participants underwent three submaximal contractions to adapt to the test. Participants were told to perform maximal effort only during extension of isokinetic testing. Peak torque values (Nm) obtained during the maximal contractions in each repetition were recorded, and the mean value was calculated. US imaging was obtained and recorded from start to end during each contraction, but architectural parameters were calculated only at knee angle where peak torque occurred during isokinetic and at the moment where peak torque was attained during isometric contractions. In the first three repetitions, the pennation angles, and in the last three repetitions the thickness and/or cross-sectional areas of the vastus medialis, vastus lateralis and rectus femoris muscles were measured. The knee joint angle of the maximal concentric torque during the isokinetic strength test was also noted.

Evaluation of muscle architecture

Morphological evaluations (muscle thickness, pennation angle, and cross-sectional) of the vastus medialis, vastus lateralis and rectus femoris were performed by the same physican using a diagnostic ultrasound (US) system (SonoScape Co. Ltd., Model S2, China) with a linear array probe (60 mm, 5-10 MHz). Measurements were applied during rest while the muscles were fully relaxed, and at the time of maximal isometric and isokinetic contractions. The knee joint was in extended (0°) and flexed position (60° of knee flexion) during the relaxed US measurements. Since multiple measurements were taken at different time points from the same muscle group, the areas where the US probe was placed during the first measurement were marked with an indelible pen. In this way, the US probe was always placed in the same area, ensuring that all US evaluations were taken from the same location for each muscle group (Figure 1). US images were obtained for the vastus medialis muscle just above and medially from the patella, for the vastus lateralis muscle in the middle between the patella and greater trochanter and slightly lateral to the midline, and lastly, for the rectus femoris muscle at 60% of the thigh length from the upper patella line to the greater trochanter (Figure 1).

Figure 1. The locations for evaluation of the vastus medialis (1), vastus lateralis (2), and rectus femoris (3) by ultrasonography.

A slight pressure was applied on the skin with the US probe to cause no muscle deformation. While evaluating pennation angle, the US probe was held in the sagittal longitudinal plan so that it was parallel to the direction of the muscle fibers. Pennation angle was determined from the insertion of the muscle fascicle to the deep aponeurosis (Figure 2a). Three different pennation angles in one image were measured and the mean value was calculated. The axial or short axis US examination was performed by rotating the probe 90° at the location where the US probe was placed for the longitudinal scan. Cross-sectional area and thickness of the muscles were measured in the axial plane. Maximum muscle thickness was determined by measuring the distance from the widest part between the superficial and deeper aponeurosis (Figure 2b). Cross-sectional area evaluations could only be made in the rectus femoris muscle due to the limited length of the US probe while taking the axial image (Figure 2c).

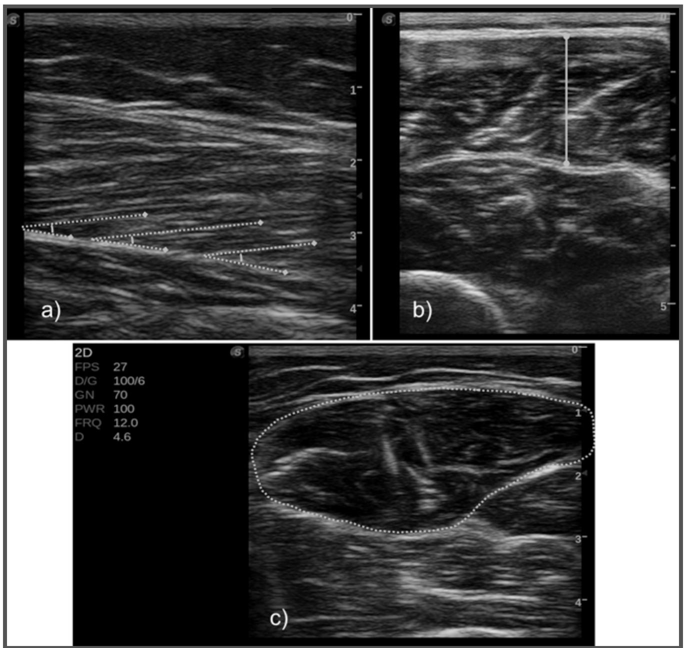

Figure 2. DPennation angle in the vastus lateralis muscle (a), thickness measurement in the vastus lateralis muscle (b), and calculation of the cross-sectional area in the rectus femoris muscle (c).

Reliability of ultrasound measurements

Measurements were repeated one day and one week later by the same researcher (US) in 12 of the male subjects who participated in the study (n=20) to test the "intra-observer" reliability of US measurements. Since there was only a strong relation between strength parameters and ultrasound measurements for muscle thickness and cross-sectional area of the rectus femoris muscle, only the rectus femoris muscle was included for reliability measurements. Meanwhile, the researcher could not see the previous results. Reliability evaluation between the two measurements (baseline-one day after and baseline-one week after) was made by calculating the intraclass correlation coefficient (ICC) using the "Two-Way Mixed" model. ICC values between 0.90-0.99, 0.80-0.89, 0.70-0.79, and below 0.69 indicate high, good, medium, and bad reliability, respectively (19). Table 1 shows the mean±SD values for muscle thickness and cross-sectional area of the rectus femoris muscle and the ICC scores between the measurements. The ICC scores between baseline and day 1 were between 0.90 and 0.99 for muscle thickness and between 0.97 and 0.99 for cross sectional area. Similarly, the ICC scores between baseline and day 7 were between 0.90 and 0.99 for muscle thickness and between 0.96 and 0.99 for cross sectional area. The stability of all measurements was assessed using the independent sample *t*-test. There were no statistically significant differences between all tests ($p>0.05$).

Statistical analysis

Statistical analysis was performed using SPSS v.23.0 (IBM SPSS Statistics) software. Mean±standard deviation was used in the descriptions of all variables. The level of significance was accepted as p <0.05. The formula "[(after - before) / before x 100]" was used in the percentage change calculations. Shapiro-Wilk test was used to evaluate the normality of the distribution of all data. Data that showed normal distribution was analyzed using the one-way ANOVA test, and data that was not normally distributed was analyzed using the Kruskal-Wallis test. Post-hoc analyzes were performed with the Bonferroni test. The relationship between parameters of muscle architecture (pennation angle, muscle thickness, cross-sectional area) and muscle strength (isometric and isokinetic strength) were determined by Pearson product-moment correlation coefficient (Spearman's rho correlation coefficient was used for non-normally distributed parameters). Correlation was accepted as weak for correlation coefficient (r) values <0.3, moderate between 0.3 and 0.7, and strong when >0.7 (19). A stepwise linear regression analysis was applied to create a predictive model for isometric and/or isokinetic strength. For each of the dependent variable (isometric and isokinetic strength) all the measured architectural variables (pennation angle, muscle thickness, and cross-sectional area) of the vastus medialis, vastus lateralis, and rectus femoris muscle were selected as independent variable. The determined parameters were included in the stepwise regression analysis as an independent variable if they provided a statistically significant contribution to the explained variance (F to inclusion ≤0.050 and F to exclusion ≥0.100).

Table 1. Reliability values of ultrasound measurement data for muscle thickness and cross sectional area of the rectus femoris muscle (mean ± SD).

	1st Test (I)	2nd Test (II)	3rd Test (III)	ICC (I-II)	*P* value (I-II)	ICC (I-III)	*P* value (I-III)
MT60 (mm)	25.3±3.3	26.6±3.8	25.8±2.9	0.90	0.471	0.90	0.761
MTIM (mm)	32.8±4.1	33.2±4.3	32.5±4.2	0.99	0.874	0.99	0.887
MTIK30 (mm)	32.5±4.4	32.6±3.1	32.2±3.6	0.94	0.985	0.98	0.884
MTIK60 (mm)	32.2±4.5	32.2±4.3	31.1±4.1	0.99	0.978	0.96	0.599
CSA60 (mm²)	80.6±11.8	83.2±13.7	85.9±14.7	0.97	0.690	0.96	0.444
CSAIM60 (mm²)	134.2±17.7	132.1±20.1	132.6±18.9	0.99	0.827	0.99	0.861
CSAIK30 (mm²)	131.9±16.7	128.5±15.4	128.8±14.0	0.98	0.678	0.96	0.691
CSAIK60 (mm²)	133.3±18.7	129.9±17.2	130.9±17.3	0.98	0.716	0.97	0.800

MT= Muscle thickness, **CSA**= Cross sectional area, **60**= Knee relaxed during 60° flexion, **IM**= Isometric contraction, **IK30**= Isokinetic contraction at 30°/sec, **IK60**= Isokinetic contraction at 60°/sec, **ICC**= Intraclass correlation coefficient.

RESULTS

Muscle architecture

Table 2. presents the architectural properties of the vastus medialis, vastus lateralis and rectus femoris muscles during relaxed and contracted conditions where peak torque was achieved. Pennation angle and muscle thickness were greater in the vastus medialis compared to vastus lateralis and rectus femoris muscles during all conditions (p<0.001). Rectus femoris muscle thickness was also greater compared to the vastus lateralis, but only in the contracted positions (p<0.01-0.001). The average peak torque for the isometric and isokinetic strength at 30°/sec and 60°/sec angular velocity was 172.3±58.8 Nm, 162.7±50.8 Nm and 142.3±44.1 Nm, respectively. The knee joint angle where the peak torque was produced and the US image was obtained in the isokinetic contraction mode was 68.2°±3.8° for the angular velocity of 30°/sec and 64.4°±4.7° for the angular velocity of 60°/sec.

Changes during muscle contractions

The increase in the pennation angle of the rectus femoris was higher only than the vastus lateralis during the isometric contraction in relation to the 0° and 60° relaxed condition and during the isokinetic contraction at 30°/sec angular velocity in relation to the 0° relaxed condition (p<0.001, Figure 3a). Furthermore, the rectus femoris exhibited the greatest change compared to the vastus medialis and vastus lateralis from the 60° relaxed to the isokinetic contracted position at 30°/sec angular velocity (p=0.006 for vastus medialis and p<0.001 for vastus lateralis), and from the 0° (p=0.039 for vastus medialis and p<0.001 for vastus lateralis) and 60° (p=0.003 for vastus medialis and p<0.001 for vastus lateralis) relaxed to the isokinetic contracted position at 60°/sec angular velocity (Figure 3a). Similarly, muscle thickness in the rectus femoris presented the most increase than the vastus medialis and vastus lateralis from the both relaxed to all the contracted conditions (p<0.001, Figure 3b).

Relationships between muscle architecture and muscle strength

Table 3. presents the correlation coefficients (r) between the muscle architecture variables and the muscle strength. Although pennation angle, muscle thickness and cross sectional area variables measured during relaxed and contracted position were moderately correlated with the isometric and isokinetic strength parameters in the vastus medialis (r=0.33-0.64, p<0.05-0.01) and vastus lateralis (r=0.11-0.68, p<0.05-0.01) muscle, muscle thickness (r=0.74-0.80, p<0.001) and cross sectional area (r=0.71-0.80, p<0.001) in the rectus femoris calculated during the relaxed and contracted condition were strongly correlated with isometric and isokinetic strength.

Table 2. Muscle architecture of the vastus medialis, vastus lateralis ve rektus femoris muscles (mean ± SD).

		Vastus Medialis	Vastus Lateralis	Rektus Femoris
PA (°)	0°	31.9±6.5	16.7±2.8***	14.6±2.9***
	60°	28.7±5.5	14.6±2.5***	12.9±2.1***
	IM	42.0±8.1	19.4±4.0***	20.8±5.1***
	IK30	40.5±7.4	18.7±2.6***	20.2±5.3***
	IK60	39.3±6.9	18.5±2.2***	20.4±5.7***
MT (mm)	0°	31.8±6.8	20.9±4.1***	20.3±4.5***
	60°	31.8±6.7	22.4±4.9***	21.5±4.9***
	IM	36.9±6.4	23.5±4.3***	28.2±6.1***,§§§
	IK30	35.4±7.3	23.8±4.3***	28.2±6.0***,§§
	IK60	35.0±6.6	23.4±4.2***	28.0±6.0***,§§
CSA (mm^2)	0°	83.3±19.6	67.8±17.0***	65.1±19.1***
	60°	79.4±20.1	76.5±17.2	68.8±20.5***
	IM			106.7±35.0
	IK30			105.0±35.8
	IK60			106.5±34.0

***p<0.001 (compared to vastus medialis), §§p<0.01 (compared to vastus lateralis), §§§p<0.001 (compared to vastus lateralis)

PA= Pennation angle, **MT**= Muscle thickness, **CSA**= Cross sectional area, **0°**= Knee relaxed during 0° flexion, **60°**= Knee relaxed during 60° flexion, **IM**= Isometric contraction, **IK30**= Isokinetic contraction at 30°/sec, **IK60**= Isokinetic contraction at 60°/sec

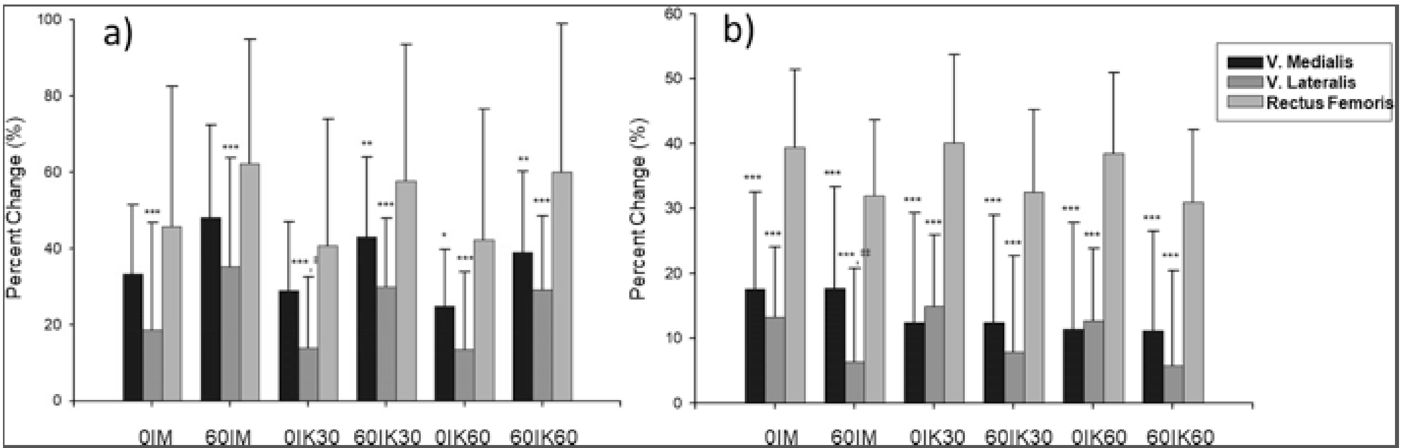

Figure 3. Percent changes in the pennation angle (a) and muscle thickness (b) of the vastus medialis, vastus lateralis, and rectus femoris muscles between the relaxed (knee 0° and 60° flexion) and contracted condition at the peak torque angle during isometric and isokinetic contractions. **p<0.05 (compared to rectus femoris), **p<0.01 (compared to rectus femoris), ***p<0.001 (compared to rectus femoris), ‡p<0.05 (compared to vastus medialis), ‡‡p<0.01 (compared to vastus medialis).*
0IM = change between the measurement of 0° knee flexion and peak isometric strength, 60IM = change between the measurement of 60° knee flexion and peak isometric strength, 0IK30 = change between the measurement of 0° knee flexion and peak isokinetic strength at 30°/sec angular velocity, 60IK30 = change between the measurement of 60° knee flexion and peak isokinetic strength at 30°/sec angular velocity, 0IK60 = change between the measurement of 0° knee flexion and peak isokinetic strength at 60°/sec angular velocity, 60IK60 = change between the measurement of 60° knee flexion and peak isokinetic strength at 60°/sec angular velocity.

Regression analysis

Table 4. shows a summary of the stepwise linear regression analysis. Only the independent variables that statistically significant contribution to the explained variance and entered the regression analysis are presented. The muscle architectural variables of the vastus medialis and vastus lateral muscles entered the model with coefficients of determination of 0.316 to 0.464 for isometric and isokinetic strength (p<0.001). On the other hand, the coefficients of determination of the cross-sectional area of the rectus femoris muscle measured at 60° relaxed position were higher for the isometric strength (R^2=0.532, Figure 4a) and isokinetic strength at 30°/sec (R^2=0.610, Figure 4b) and 60°/sec

(R^2=0.557, Figure 4c) angular velocities. Similarly, rectus femoris muscle thickness during isometric (R^2=0.538 for isometric strength, Figure 4d) and isokinetic (R^2=0.600 for 30°/sec and R^2=0.561 for 60°/sec, Figure 4e and Figure 4f) contractions entered the model also with higher coefficient of determinations (p<0.001).

Table 3. Correlation between the peak isometric and isokinetic strength and architectural features of the vastus medialis, vastus lateralis and rectus femoris muscles during relaxed and contracted conditions.

		(*r* value)	Isometric	Isokinetic (30°/sec)	Isokinetic (60°/sec)
Vastus Medialis	Pennation angle	Relaxed (0°)	.46**	.49**	.48**
		Relaxed (60°)	.56**	.64**	.60**
		Isometric	.48**	-	-
		Isokinetic (30°/sec)	-	.60**	-
		Isokinetic (60°/sec)	-	-	.59**
	Muscle Thickness	Relaxed (0°)	.39*	.52**	.54**
		Relaxed (60°)	.33	.43*	.47**
		Isometric	.49**	-	-
		Isokinetic (30°/sec)	-	.44**	-
		Isokinetic (60°/sec)	-	-	.45**
	Cross Sectional Area	Relaxed (0°)	.49**	.48**	.49**
		Relaxed (60°)	.49**	.50**	.50**
Vastus Lateralis	Pennation angle	Relaxed (0°)	.11	.24	.24
		Relaxed (60°)	.35	.40*	.36*
		Isometric	.40**	-	-
		Isokinetic (30°/sec)	-	.52**	-
		Isokinetic (60°/sec)	-	-	.44**
	Muscle Thickness	Relaxed (0°)	.61**	.67**	.66**
		Relaxed (60°)	.51**	.61**	.59**
		Isometric	.59**	-	-
		Isokinetic (30°/sec)	-	.68**	-
		Isokinetic (60°/sec)	-	-	.58**
	Cross Sectional Area	Relaxed (0°)	.38*	.42**	.40*
		Relaxed (60°)	.62**	.61**	.57**
Rectus Femoris	Pennation angle	Relaxed (0°)	.21	.24	.11
		Relaxed (60°)	.19	.22	.12
		Isometric	.49**	-	-
		Isokinetic (30°/sec)	-	.45**	-
		Isokinetic (60°/sec)	-	-	.35*
	Muscle Thickness	Relaxed (0°)	.75***	.80***	.77***
		Relaxed (60°)	.75***	.77***	.74***
		Isometric	.77***	-	-
		Isokinetic (30°/sec)	-	.79***	-
		Isokinetic (60°/sec)	-	-	.78***
	Cross Sectional Area	Relaxed (0°)	.75***	.78***	.78***
		Relaxed (60°)	.80***	.80***	.79***
		Isometric	.73***	-	-
		Isokinetic (30°/sec)	-	.78***	-
		Isokinetic (60°/sec)	-	-	.71***

*p<0.05, **p<0.01, ***p<0.001

DISCUSSION

We investigated relationships between architecture of quadriceps muscle depicted by ultrasonography and its isometric and isokinetic strength. The main result of the present study is that rectus femoris muscle thickness and cross-sectional area evaluated during relaxed or maximal contracted conditions are associated with isometric and isokinetic knee extensor strength.

The muscle architectural measurements obtained in the current study agree well with measurements of the quadriceps muscle evaluated in previous studies using sonography. The pennation angles measured with ultrasound of the rectus femoris and vastus lateralis while knee joint fully relaxed and in 0° (RF=14.6°, VL=16.7°) and 60° (RF=12.9°, VL=14.6°) of flexion were similar as to previous studies that measured pennation angles in these muscles while knee in 0°-20° (RF=15.9°, VL=12.5°-14.7°) and 60° (RF=10°-17°, VL=11.9°-14.5°) of flexion (7-9, 14, 17). The reason of higher pennation angle in the vastus medialis muscle (0° flexion=31.9°, 60° flexion=28.7°) in this study than the previous studies (0° flexion=12.1°-13.8°, 60° flexion=15°-17°) might be due to the location where ultrasonography was performed. We obtained images from the more distal part of the vastus medialis muscle, while US measurements in previous studies were taken from the mid-thigh (14-17) or 1/3 below the distance between the knee joint and the greater trochanter (7), where muscle fibrils are more parallel. On the other hand, the muscle thickness values for all the three muscle groups (RF=20.3 mm in 0° and 21.5 mm in 60°, VL=20.9 mm in 0° and 22.4 mm in 60°, VM=31.8 mm in 0° and 60°) measured in relaxed position in our study were similar to previous studies. Muscle thickness in the rectus fe–

moris, vastus lateralis and vastus medialis was 18.1 mm, 22.6 - 25.4 mm, and 29.9 mm, respectively, when knee joint was at 0° - 20° flexion (17, 20-22): it was 23 mm, 26 mm, and 30 mm when knee joint was at 60°-90° flexion (7) in these previous studies.

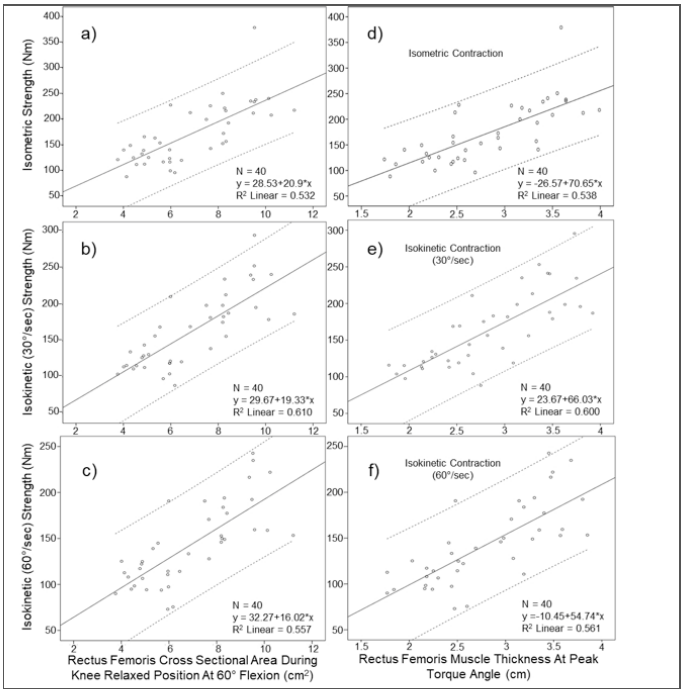

Figure 4. Scatterplots of mean subject data with regression lines and 95% confidence interval of regression lines, showing the relationship between maximal strength and the rectus femoris cross-sectional area measured by ultrasonography during knee relaxed position at 60˚ knee flexion ((a) isometric strength, (b) isokinetic 30˚/sec strength, and (c) isokinetic 60˚/sec) and the rectus femoris muscle thickness at peak torque angle during contractions ((d) isometric strength, (e) isokinetic 30˚/sec strength, and (f) isokinetic 60˚/sec).

There are small numbers of studies available in the literature that evaluated quadriceps muscle architecture during contraction (8, 23). These performed ultrasonography generally during isometric contraction when knee joint was at 60°and 90° of flexion (8, 23). The pennation angles in the rectus femoris (20° and 26°) and vastus lateralis (17.5°) muscle measured during isometric contraction and knee in 60° of flexion were similar to our results (RF=22.8°, VL=20.8°). However, Massey et al. (8) found a lower pennation angle in the vastus medialis muscles (22°) compared to our results (42°). As previously mentioned, this difference might have been resulted from the images of the vastus medialis taken more distally and close to the vastus medialis oblique muscle section. As the change between rest and maximal contraction was taken into consideration, the highest increase was in the rectus femoris muscle with 40-62% in pennation angle and 31-40% in muscle thickness. The pennation angle represented 24-48% and 13-35% increase and muscle thickness 11-17% and 6-14% increase in the vastus medialis and vastus lateralis muscle, respectively. The increases in pennation angle from rest to isometric contraction (VL=24.1%, VM=45.1% and RF=58.6%) in the present study were similar to the study of Massey et al (8).

The majority of studies investigating the relationship between muscle architecture and muscle strength correlated resting muscle architectural structure data with peak isometric torque (7-9, 14, 17, 20, 21, 24-28). The knee joint was generally either in 0°-20° (14, 17, 20, 21, 25-28) or 90° (7, 9) of flexion during the ultrasonography in the relaxed quadriceps muscle. However, quadriceps muscle strength curve revealed that the maximum torque was achieved at 60° flexion during knee extension (18). For this reason, if the measurements will be carried during relaxed condition, it is more accurate to do this at 60° of knee flexion and correlate it with muscle strength. In addition to 0 of knee flexion the present study evaluated resting quadriceps muscle architecture also at 60° of knee flexion and found a moderate correlation between the peak isometric and isokinetic torque and the pennation angle (r=0.46-0.64), muscle thickness (r=0.39-0.54), and cross-sectional area (r=0.49-0.50) of the resting vastus medialis, and muscle thickness (r=0.51-0.67) and cross-sectional area (r=0.38-0.62) of the resting vastus lateralis. On the other hand, muscle thickness (r=0.75-0.80) and cross-sectional area (r=0.75-0.80) of the rectus femoris had a strong correlation. Although in different knee positions as the present study, either in near full extension or 90° flexion, previous studies also represented moderate to strong correlations between muscle thickness or cross sectional area measurements and isometric strength measured at knee 90° of flexion. Correlation with pennation angle, on the other hand was low to moderate in these studies (7, 9, 14, 17, 21, 25, 26).

A unique aspect of the current study is the simultaneous sonographic evaluations of the quadriceps muscle during maximal isometric and isokinetic contractions. As far as we know, there are only two studies in the literature that investigated muscle architecture during contractions, one in the quadriceps (8) and the other in the erector spinae (29), and correlated this with peak torque. Both studies preferred the isometric contraction mode. Massey et al. found a moderate relationship (r=0.530) between the maximal isometric torque and quadriceps cross-sectional area during maximal isometric contraction (8). Cuesta-Vargas & Gonzalez-Sanchez revealed a moderate relationship with maximal strength and muscle thickness and pennation angle in the right and left erector spinae measured during contraction

(29). When the current literature is scrutinized, the present study is the first reporting the relationship between quadriceps muscle architecture during isokinetic contraction and peak isokinetic torque. The most remarkable finding in the current study was the strong correlation of the rectus femoris muscle thickness and cross-sectional area measured at peak torque production with the peak isometric (r=0.73-0.77) and isokinetic (r=0.71-0.79) torque. On the other hand, a moderate correlation was found between the peak torque values and pennation angle values of all three muscles (r=0.40-0.49 for isometric and r=0.44-0.60 for isokinetic) and muscle thickness values of vastus medialis and vastus lateralis muscle (r=0.49-0.59 for isometric and r=0.44-0.68 for isokinetic).

Table 4. Data on stepwise linear regression analysis to predict the peak isometric and isokinetic knee extension strength with architectural variables of the vastus medialis, vastus lateralis and rectus femoris muscles evaluated with sonography.

Independent variables	Multiple regression equation	*R*	R^2	*P*
X_1:VM-PA-60	Isometric = 1.378 + 5.967*X_1	0.562	0.316	<0.001
X_1:VM-PA-60	Isokinetic (30˚/sec) = -6.409 + 5.903*X_1	0.644	0.414	<0.001
X_1:VM-PA-60	Isokinetic (60˚/sec) = 8.913 + 4.665*X_1	0.586	0.344	<0.001
X_1:VL-CSA-60	Isometric = 11.096 + 21.073*X_1	0.615	0.378	<0.001
X_1:VL-MT-IK30	Isokinetic (30˚/sec) = -27.201 + 79.681*X_1	0.681	0.464	<0.001
X_1:VL-MT-0	Isokinetic (60˚/sec) = -6.616 + 71.413*X_1	0.659	0.435	<0.001
X_1:VL-CSA-60 X_2:VL-MT-0	Isometric = -32.239 + 13.242*X_1 + 49.429*X_2	0.665	0.443	<0.001
X_1:VL-CSA-60 X_2:VL-MT-0 X_3:VL-PA-0	Isometric = 33.717 + 16.366*X_1 +66.798*X_2 - 7.558*X_3	0.732	0.536	<0.001
X_1:RF-CSA-60	Isometric = 28.525 + 20.895*X_1	0.729	0.532	<0.001
X_1:RF-CSA-60	Isokinetic (30˚/sec) = 29.667 + 19.334*X_1	0.781	0.610	<0.001
X_1:RF-CSA-60	Isokinetic (60˚/sec) = 32.272 + 16.025*X_1	0.746	0.557	<0.001
X_1:RF-MT-IM	Isometric = -26.569 + 70.655*X_1	0.733	0.538	<0.001
X_1:RF-MT-IK30	Isokinetic (30˚/sec) = -23.670 + 66.032*X_1	0.774	0.600	<0.001
X_1:RF-MT-IK60	Isokinetic (60˚/sec) = -10.451 + 54.742*X_1	0.749	0.561	<0.001
X_1:RF-MT-IK30 X_2:VL-MT-0	Isokinetic (30˚/sec) = -63.351 + 49.682*X_1 + 41.090*X_2	0.819	0.671	<0.001
X_1:RF-MT-IK60 X_2:VL-MT-0	Isokinetic (60˚/sec) = -44.283 + 40.367*X_1 + 35.430*X_2	0.793	0.630	<0.001

VM= Vastus medialis, **VL=** Vastus lateralis, **RF=** Rectus femoris, **PA=**Pennation angle, **MT=**Muscle thickness, **CSA=**Cross sectional area, **0=**During knee relaxed at 0˚ knee flexion, **60=**During knee relaxed at 60˚ knee flexion, **IM=**During peak isometric strength, **IK30=** At the knee joint angle where peak isokinetic strength during 30˚/sec angular velocity is achieved, **IK60=** At the knee joint angle where peak isokinetic strength during 60˚/sec angular velocity is achieved.

The present study also examined the determination coefficients of regression analysis to estimate what proportion of the torque could be explained by architectural variables. The analysis showed that peak isometric and isokinetic strength could be explained by 31.6-46.4% with muscle architecture variables of vastus medialis and vastus lateralis. On the other hand, the prediction rate increased to 53.2% and 55.7-61.8% with the cross-sectional area measurements of the rectus femoris during rest at 60° of knee flexion for isometric and isokinetic torque, respectively. Furthermore, the rectus femoris muscle thickness measured at the peak torque production could estimate isometric peak torque for 53.8% and isokinetic peak torque for 56.1 - 61.0%. When the vastus lateralis muscle thickness was added to the rectus femoris muscle thickness, which were measured at the point where the isokinetic peak torque was obtained, the ratio increased to 67.1% in estimating the isokinetic strength. Ando et al. stated that the strength variance during maximal voluntary contraction could be estimated by 91% with the combination of vastus intermedius muscle thickness and pennation angle measured at rest (7). Since vastus intermedius muscle was not included in our study, it was not possible to compare it with the current study. Raj et al. expressed that muscle thickness of the rectus femoris and vastus intermedius in non-contracted condition could be determinant in 63% for peak isometric torque and 57%-68% for peak isokinetic torque (9).

Study Limitations

One of the limitations of the present study was that only the cross-sectional area of the rectus femoris could be measured during isometric and isokinetic contractions because extrapolation outside the field of view of the ultrasound transducer was necessary in many cases to evaluate cross-sectional area of the other muscle bellies. In addition, the vastus intermedius muscle has not been included in this study.

CONCLUSION

The present study illustrated that muscle thickness and cross-sectional area of the rectus femoris muscle measured either in relaxed or contracted condition have a moderate to high impact on the variance exerted on the torque during maximal isometric or isokinetic knee extension. The results suggest that rectus femoris muscle thickness and cross-sectional area obtained during ultrasound has the potential to be used for evaluating quadriceps isometric and isokinetic strength. There is a need to investigate the change in muscle architecture, especially in muscle thickness and cross-sectional area with long-term strengthening programs.

Acknowledgement / Teşekkür

This research was supported by the Scientific and Technological Research Council of Turkey (TUBİTAK); project number: 118S657.

Ethics Committee Approval / Etik Komite Onayı

The approval for this study was obtained from the Institutional Ethics Committee of Bursa Uludağ University, Bursa, Turkey (Decision no: 2018-4/37 Date: 20.02.2018).

Conflict of Interest / Çıkar Çatışması

The authors declared no conflicts of interest with respect to authorship and/or publication of the article.

Financial Disclosure / Finansal Destek

This research was supported by the Scientific and Technological Research Council of Turkey (TUBİTAK); project number: 118S657.

Author Contributions / Yazar Katkıları

Concept US; Design US; Supervision All authors; Materials US, UCY; Data Collection and/or Processing US,UCY; Analysis and Interpretation US; Literature Review US, UCY; Writing Manuscript US, UCY; Critical Reviews All authors.

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