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ORIGINAL SCIENTIFIC PAPER

Relationship between Rectus Femoris Muscle Architecture and Isokinetic Peak Knee Extension Torque in Physically Active Men

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Abstract

The aim of this study was to examine the relationship between rectus femoris muscle architecture and isokinetic concentric peak knee extension torque at various velocities. Twenty physically active men (age =21.1±1.41 years, weight =69.9±5.7 kg, height =176.4±7.07 cm) had their isokinetic concentric knee extensor (Biodex 4 Pro, Biodex Medical Inc, Shirley, USA) strength assessed at 60°/sec, 180°/sec and 300°/sec. Pennation angle, muscle thickness, and fascicle length of the rectus femoris was measured using real-time B-mode ultrasound (Logiq P5, GE Healthcare, UK). Pennation angle had a significant positive correlation to peak torque at 60°/sec (r=0.731, p=0.001), 180°/sec (r=0.802, p=0.001) and 300°/sec (r=0.685, p=0.001). There was a significant positive correlation between muscle thickness and peak torque at 60°/sec (r=0.718, p=0.001), 180°/sec (r=0.749, p=0.001) and 300°/sec (r=0.722, p=0.001). However, there was no significant correlation between fascicle length and the isokinetic peak torque values (p>0.05). In addition, pennation angle and muscle thickness were found to be significant contributors for predicting isokinetic knee extension torque (R2=0.47-0.64; p<0.01). Pennation angle and muscle thickness best predicted peak knee extension torque at 180°/sec (explained variance =64% and 56%, respectively). This study suggests that pennation angle and muscle thickness can be used to predict isokinetic knee extension torque in physically active men.

Keywords: *football, isokinetic, ultrasound, skeletal muscle*

Introduction

The measurement of muscular strength is of clinical significance given its relationship to morbidity rates in males (Ruiz et al., 2008) and injury risk identification (Duhig et al., 2019; Van Dyk et al., 2016; Zinke, Warnke, Gäbler, & Granacher, 2019). Isokinetic dynamometry is the gold standard in strength assessment and provides reliable measures of joint torque (Brown & Greig, 2024; Verdijk, Van Loon, Meijer, & Savelberg, 2009). However, maximal isokinetic strength assessment can be challenging. It requires a skilled technician, familiarization period and is expensive. One alternative to the aforementioned challenges is the use of surrogate measure such as ultrasonography, which can be used to assess muscle function. Ultrasound examination is a simple, non-invasive solution for measuring the architectural features of muscles, but it also requires an experienced technician (Chauhan, Hamzeh, & Cuesta-Vargas, 2013).

Muscle architecture consists of pennation angle, muscle thickness and fascicle length (Coratella et al., 2020) and plays a pivotal role in muscle performance. The architectural characteristics have an effect on force generation and speed of contraction of the muscle-tendon unit (De Boer

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et al., 2008; Lieber, 2010; Nuell et al., 2021). Increasing or decreasing in parallel sarcomeres leads to greater or lesser pennation angles which affects the physiological cross-sectional area and in turn increases or decreases force generation (Cunnane et al., 2023; Dias et al., 2016). The fascicle length directly affects the force-velocity performance and the force transferred to tendons (Abe, Fukashiro, Harada, & Kawamoto, 2001). The relationship between ultrasound measures of quadriceps muscle thickness and pennation angle is well established (Abe, Kojima, & Stager, 2014; Cadore et al., 2012; Fukumoto et al., 2011; Strasser, Draskovits, Praschak, Quittan, & Graf, 2013, Watanabe et al., 2013). Raj, Bird and Shield (2017) have shown that quadriceps muscle thickness is a robust predictor of knee extensor strength in older adults, however, there is limited research examining the relationship between muscle architecture and strength at isokinetic velocities. The role muscle architecture plays in force production is recognized, although further exploration on its influence on joint velocity is warranted.

The aim of this study is to examine the relationship between rectus femoris architecture and knee extension torque at various velocities. We hypothesized that (i) muscle architecture would have a significant positive correlation with knee extension torque, and (ii) muscle architecture can be used as an independent contributor to peak torque prediction models.

Methods

Experimental Design

In this study, we used a cross-sectional study design to examine whether there is a relationship between rectus femoris muscle architecture and peak torque during a concentric isokinetic knee extension at various velocities. Each participant visited the clinic on three separate days at approximately the same time. During the first visit, the participants were familiarized with the whole isokinetic dynamometer protocol before the actual testing days. The participants' anthropometric measurements were taken on the same day. The second visit occurred at least 48 hours later to avoid morphological acute changes that may have occurred after the familiarization session. At the second visit, a 2D real-time B-mode ultrasound was performed by a musculoskeletal physician with more than 10 years of experience in musculoskeletal ultrasound analysis to determine the pennation angle, muscle thickness and fascicle length of the dominant leg of the rectus femoris muscle. During the third visit, isokinetic dynamometer strength assessments were performed at 60°/sec, 180°/sec and 300°/sec.

Participants

Twenty healthy and physically active men took part in this study (age = 21.1±1.4 yrs, weight = 69.9±5.7 kg, height = 176.4±7.07 cm). Sixty percent of the participants played football (n=12), 20% volleyball (n=4) and 20% basketball (n=4). Participants' training status (experience and training volumes) are presented in Table 1. The inclusion criterion was that they had been exercising for ≥5 years, while the exclusion criteria for participants included current or previous musculoskeletal injuries and a history of lower limb surgery. Sample size was determined by a priori power analysis using G-Power (3.1.9.3). The effect size was based on previous studies that reported a coefficient of determination between the combined rectus femoris and vastus intermedius thickness and maximal isometric knee extension at 60°/sec (R2 = 0.60) (Raj et al., 2017). An effect size of 0.77 was considered a reasonable and conservative point for determining the sample size. The type I error (α) was 0.05, and power (1-β) 0.80 with a two-tail bivariate normal model. The model indicated a minimum total sample size of 10 participants, but considering a miss rate, we decided to have a total of 20 participants. All participants were informed of the benefits and risks of the investigation prior to signing an institutionally approved informed consent document to participate in the study. This study was approved in advance by Research Ethics Committee of Inonu University (approval number: 2017/61). Each participant voluntarily provided written informed consent before participating.

Body Composition Measurements

All measurement procedures were performed with minimal clothing (e.g. shorts, underwear, no shoes and with jewellery removed). Participants' height was measured with a portable stadiometer (Seca Ltd., Bonn, Germany) with an accuracy of 0.1 cm, with the head in the Frankfort plane, while the body was upright and weight evenly distributed across both legs. Body mass and body fat percentage were measured using a body composition scale with a capacity of 270 kg and a sensitivity of 100 g (Tanita SC-330S, Amsterdam, The Netherlands).

Muscle Architecture Measurements

Architecture was assessed using 2D real-time B-mode ultrasound device (Logiq P5, GE Healthcare, UK) with a 4.5 cm linear array transducer (frequency 10-MHz and depth 5 cm). Imaging was conducted supine, with the rested leg supported in passive extension. Rectus femoris pennation angle, muscle thickness and fascicle length were measured with the probe placed transversely and longitudinally. The transducer was placed with adequate use of contact gel and minimal pressure to avoid excessive compression of the muscle at 50% of the distance from the superior border of the patella and great trochanter. Pennation angle was determined as the angle between the muscle fascicles and the deep aponeurosis. Muscle thickness was determined as the distance between the superficial and deep aponeurosis. Fascicle length across the deep and superficial aponeurosis was estimated from isolated muscle thickness and angle using the following equation:

fascicle length=muscle thickness-sinα-1

where α is the pennation angle of the muscle as determined by ultrasound (Kawakami, Abe, Kuno, & Fukunaga, 1995). All measurements were carried out by the same experienced sonographer who was blinded to participants. Three ultrasound images were taken from each trial in order to increase the reliability and the average of the three values for each variable was used for statistical analysis (Kwah, Pinto, Diong, & Herbert, 2013). The images were assessed using software in-built in the Ultrasound Device, real time. Intrarater reliability for muscle architecture was evaluated using intra-class correlation coefficient (ICC), coefficient of variance (CV), and standard error of mean (SEM). The ICCs were 0.997, 0.999 and 0.989 for pennation angle, muscle thickness and fascicle length, respectively. The mean CVs and SEMs were 1.26 % and 0.50° and 0.42% and 0.07 cm and and 1.33% and 0.19 cm for pennation angle, muscle thickness and fascicle length, respectively.

Isokinetic Concentric Peak Torque Assessment

Participants were provided detailed briefing before data collection session. Approximately 48 hours before the test, participants were informed about the isokinetic dynamometer and a familiarization trial conducted. Concentric isokinetic peak torque test of the dominant leg (based on kicking preference) was measured with the use of a dynamometer (Biodex 4 Pro, Biodex Medical Inc, Shirley, USA). The control strap was secured over the chest and abdominal area to minimize the motion of the upper body and to avoid compensatory movement (Feiring, Ellenbecker, & Derscheid, 1990). The lever range of motion was set between 0° to 100° flexion. Prior to the testing protocol, a warm-up consisting of four repetitions of 50% maximal effort was performed at each speed (300°/sec, 180°/sec, 60°/sec) (Mota et al., 2015). After warming up, participants performed four repetitions of concentric knee extension tests at different angular speeds of the dominant leg across 100 degrees knee extension (300°/sec, 180°/sec, and 60°/sec, respectively). The order of angular velocities was randomized for each participant, who performed four contractions at each speed with a 30-s rest between contractions and a 1-min rest between speeds (Raj et al., 2017). Torque values from the trials were automatically corrected for the effects of gravity by the Biodex Advantage Software program (version 4.0, Biodex Medical Inc, Shirley, USA). The highest peak torque obtained at the end of the repetitions was recorded in Newton meters (Nm).

Statistical Analysis

Statistical analyses were performed using GraphPad Prism version 7.0 (GraphPad Software, USA). All data are presented as mean ± (SD: standard deviation). The homogeneity of the study data was determined by skewness and kurtosis values (between 1.5 and -1.5) and the Shapiro Wilks test used as sample size was less than 50. The correlation between muscle architecture and isokinetic performance was evaluated by means of the Pearson product–moment correlation coefficient with 95% confidence interval. Correlation was interpreted as follows: an r between 0 and 0.3, was considered small; 0.31–0.49, moderate; 0.5–0.69, large; 0.7–0.89, very large; and 0.9–1, near perfect for relationship prediction (Hopkins, 2013). Linear regression analysis was used to determine whether the muscle architecture values predicted the isokinetic performance scores. The alpha level was accepted at $p<0.05$.

Results

Participants' demographic, training status, architectural characteristics and isokinetic peak torque values are shown in Table 1 as mean values ± standard deviations (min-max). Data were normally distributed. The isokinetic measures showed a negative trend of increasing torque as the angular velocity decreased.

Table 1. Descriptive statistics (mean ± SD; min-max) for the physical characteristics, training status, muscle architecture characteristics and isokinetic peak torque values of participants (n=20)

Physical characteristics				
Age (year)	Mass (kg)	Height (cm)	BFP (%)	BMI (kg/m2)
21.1±1.3 (19-23)	69.9±6.3 (60.6-80)	174.9±7.2 (1.61-1.86)	9.3±2.1 (5.56-12.5)	22.7±1.6 (19.56-25.31)
Training status				
Training experience (year)	Training frequency (session/week)	Training frequency (hours/week)		
7.3±1.8 (5-11)	4.3±0.9 (3-6)	5.8±1.6 (3-8.5)		
Muscle architecture characteristics				
Muscle thickness (cm)	Pennation angle (°)	Fascicle length (cm)		
3.20±0.4 (2.6- 3.8)	16.6±2.3 (13.3-21.2)	11.06±0.9 (9.9-13.2)		
Isokinetic peak torque values				
300°/sec (Nm)	180°/sec (Nm)	60°/sec (Nm)		
125.1± 25.5 (85-164.3)	154.7±30.3 (100-215)	202.9±40.6 (110-260.1)		

Note n: number of participants; BFP: body fat percentage; BMI: body mass index

Figure 1 shows a very large positive linear correlation between muscle thickness and pennation angle (r=0.801; 95% CI=0.584 to 0.922, p<0.01) and a large negative correlation between fascicle length and pennation angle (r=-0.544; 95% CI=-0.772 to -0.276, p=0.013). There was no significant relationship between muscle thickness and fascicle length (r=0.058; 95% CI=-0.333 to 0.453, p=0.807).

Figure 2 shows large and very large correlation between the pennation angle and 60°/sec (r=0.731; 95% CI=0.426 to 0.886), 180°/sec (r=0.802; 95% CI=0.557 to 0.918), 300°/sec (r=0.685; 95% CI=0.348 to 0.865). Very large correlations were found between muscle thickness and 60°/sec (r=0.718; 95% CI=0.403 to 0.880), 180°/sec (r=0.749; 95% CI=0.458 to 0.894), 300°/sec (r=0.722; 95% CI=0.410 to 0.882). However, no correlation was found between fascicle length and isokinetic peak torque values (p>0.05).

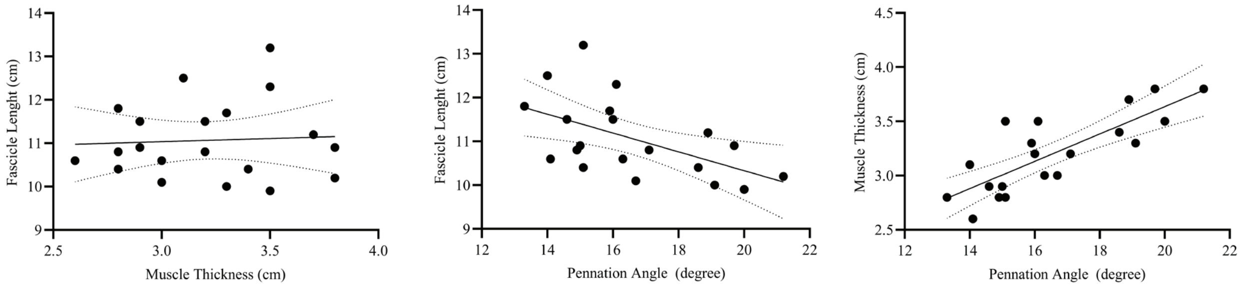

FIGURE 1. Correlation between the architectural values of the rectus femoris with linear regression line with 95% CI.

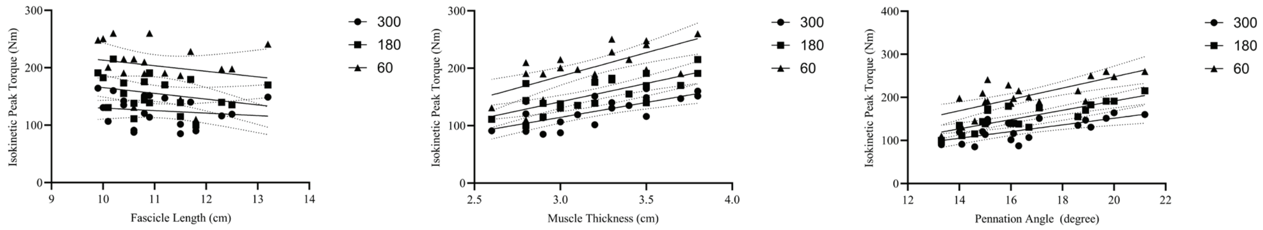

FIGURE 2. Illustrates the correlation between the isokinetic testing scores and muscle architecture. Individual data points are presented as well as linear regression line with 95% CI.

Table 2 shows that pennation angle and muscle thickness could predict peak torque (p<0.01), but fascicle length could not predict peak torque (p>0.05). Rectus femoris pennation angle was a significant independent contributor to the models predicting the isokinetic knee extensor torque at 60°/sec, 180°/sec, 300°/sec (R2=0.53, 0.64 and 0.47 respectively). In addition, rectus femoris muscle thickness was a significant independent contributor to the models predicting isokinetic knee extensor torque at 60°/s, 180°/s and 300°/s (R2=0.51, 0.56 and 0.52, respectively). Peak torque at 180°/s was best predicted when using pennation angle and muscle thickness as a single predictor with 95% CI.

Table 2. Regression constants and coefficients for relationships between muscle architecture and isokinetic strength

Dependent variables	Regression equation	R^2	Adj-R^2	p value
PT at 60°/sec (Nm)	-15.183 + 13.150 (pennation angle)	0.53	0.51	0.001*
	-59.955 + 82.015 (muscle thickness)	0.51	0.49	0.001*
	310.279 + (-9.704) (fascicle length)	0.05	0.21	0.367
PT at 180°/sec (Nm)	-23.667 + 10.757 (pennation angle)	0.64	0.62	0.001*
	-49.881 + 63.844 (muscle thickness)	0.56	0.54	0.001*
	265.591 + (-10.018) (fascicle length)	0.09	0.04	0.207
PT at 300°/sec (Nm)	-3.252 + 7.740 (pennation angle)	0.47	0.44	0.001*
	-40.796 + 51.767 (muscle thickness)	0.52	0.49	0.001*
	173.785 + (-4.398) (fascicle length)	0.02	-0.03	0.517

Note PT: Peak knee extension torque; R^2: variance explained; Adj-R^2: Adjusted R^2; * denotes significance p<0.05

Discussion

The findings from this study suggest rectus femoris pennation angle and muscle thickness are associated with peak torque across all three velocities, and muscle architecture can be used to predict isokinetic knee extensor torque in physically active men.

There is growing evidence to support the use of muscle architecture to predict strength (Abe et al., 2015; Moreau, Simpson, Teefey, & Damiano, 2010; Strasser, et al., 2013). Previous study by Raj et al. (2017) showed that combined rectus femoris and vastus intermedius thickness was a significant (p<0.05) independent contributor to predict isometric and isokinetic knee extensor torque at 60°/s (R2=0.63), 120°/sec (R2=0.68), 240°/sec (R2=0.65) and 360°/sec (R2=0.66). Trezise et al. (2016) found that vastus lateralis, vastus intermedius and rectus femoris architecture and neuromuscular variables showed the greatest effect on maximum knee extension torque (R2=0.72). Housh, Housh, Johnson and Chu (1993) reported significant (p<0.05) correlations between the isokinetic peak torque for arm flexor and muscle cross sectional area (forearm) at isometric (r=0.73), 60°/sec (r=0.85), and 120°/sec (r=0.76). Our findings further support the relationship between muscle architecture and function as they showed significant correlations between peak torque at all angular velocities (r=0.685-0.802; 47-64% explained variance). In addition, muscle architecture was a significant independent contributor to the models predicting isokinetic knee extensor torque at 60°/sec, 180°/sec, and 300°/sec (p<0.01).

Both type I and II fibers can be maximally activated at lower speeds, while the slow-twitch type I fibers initially remain passive at higher angular velocities (Iodice et al., 2020; Kannus, 1994). Therefore, it is to be expected that the torque is greater at lower speeds. It has been mentioned that all three muscle fibers type (such as Type I, IIa and IIb) contribute to force generation at low angular velocities and there is a transition towards Type IIb as the angular velocity increases (Kocahan et al., 2017). Also, it has been suggested that larger pennation angles may be associated with slower contraction velocities, and that increasing the pennation angle can negatively affect a muscle's ability to produce maximum contraction velocity (Narici, 1999; Wakeling et al., 2020). Therefore, training at low and moderate angular velocities (at 30°/sec, 60°/sec or 180°/sec, etc.) may be preferred for increasing pennation angle and muscle thickness. Conversely, lesser pennation angles increase muscle shortening velocity, as longer fibers shorten at greater absolute speeds than a similar muscle with shorter fibers (Cormie, McGuigan, & Newton, 2011). Gür, Gransberg, van Dyke, Knutsson and Larsson (2003) analyzed muscle fiber types via biopsy with participants performing isokinetic maximal contraction at 30°/sec and 240°/sec. Significant correlations were observed between both peak torque at 240°/sec and the relative type II fiber area ($r=0.46$; $p<0.05$). Furthermore, Bartolomei et al. (2001) found the existence of positive correlations between pennation angle and muscle thickness of the vastus lateralis and sprint agility test in field hockey players ($r=0.62$; $p=0.006$ and $r=0.51$; $p=0.032$, respectively). Therefore, isokinetic exercise programs performed at high angular velocities may be optimal for improving explosive power performance.

Although the muscle architecture contributes significantly to the differences in the torque, other factors also have an effect on torque performance. Factors such as microRNA3 expression and motor unit action potential amplitudes at the cellular level (Mitchell et al., 2018). Therefore, in our study, it is not surprising that only 47–64% (R2=0.47-0.64) of the variability in the torque at different angular velocities of movement is accounted for by muscle architecture.

The finding the rectus femoris fascicle length is not related to isokinetic strength does not support our hypothesis of a positive relationship between muscle architecture and strength. However, a previous study found that vastus lateralis fascicle length is related to time to peak isokinetic torque, vertical jump height and timed up and go performance, but not peak torque (Raj et al., 2017). Also, Abe et al. (2001) observed that sprinters have longer vastus lateralis and gastrocnemius medialis fascicle lengths than endurance runners. These studies imply that muscle fascicle lengths may influence muscle contraction speeds, but not necessarily muscle strength.

The study emphasizes the importance of ultrasound for athletes, which offers a more accessible and faster examination option than other imaging techniques (such as MRI or CT). In addition, our results may provide important insights into the relative importance of architectural variables for torque in isokinetic activities. However, this study is not without limitations. First, this paper conducted the research with physically active men, which may result in low generalizability in other groups (such as patient, sedentary or gender differences). Second, we only examined one fascicle of interest at a given point and this may not be truly representative of how the whole muscle performs (Charles, Kissane, Hoehfurtner, & Bates, 2022). Finally, the design of the study was cross-sectional, which does not allow the identification of which angular velocity can modify muscle architecture characteristics in the long-term. We suggest future studies focus on evaluating how isokinetic exercise can alter rectus femoris architecture. Despite these limitations muscle architecture can be used to reliably predict strength in young males.

Conclusion

Muscle architecture parameters are strongly correlated with isokinetic peak torque. This study shows the validity of the analysis of muscle architecture to predict isokinetic knee extensor torque in physically active men. We suggest the use of ultrasound to understand strength capabilities, as it is an easier and more accessible method in comparison to the isokinetic test.

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Conflict of Interest
The author declares that there is no conflict of interest.

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