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Morphometry of the harvestable surface area of quadriceps tendon using a simple tracing method: A common ACL autograft

Sabiha Latiff, Oladiran I. Olateju

School of Anatomical Sciences, Faculty of Health Sciences, University of the Witwatersrand, 7 York Road, Parktown, 2193, Johannesburg, South Africa

SUMMARY

Several tendons can be used as autografts for anterior cruciate ligament reconstruction, and the choice often depends on the surgeons' preferences. The quadriceps tendon is a commonly used autograft. This study presented, for the first time, the morphometry of the harvestable area of the QT using a simple tracing method. Adult cadavers of South Africans of European Ancestry were carefully dissected to expose the tendon. Then the tendon outline (pre-marked to enhance visibility) was then traced on a firmly secured wax paper which assumed the curvature of the tendon *in situ*. The tracing was then scanned (with its inscribed scale bar) and the morphometrics were measured on the digitized images using an imageJ software. The limb length was also measured in order to normalize all the measurements. Despite the observable difference in the surface area of the quadriceps tendon in each individual, there was no significant difference. For the other measurements, there were no side or sex differences except for the straight distal width which is sexually dimorphic. Some paired parameters showed a strong correlation but the correlation between the limb length and other measurements was weak. These data will be useful for pre-operative planning of anterior cruciate ligament reconstruction and will shed more light into the usability of the quadriceps tendon as a graft with respect to healing at the donor site and the return of knee function.

Key words: Quadriceps tendon – Morphometry – Harvestable area – Tendon tracing – Anterior cruciate ligament reconstruction

INTRODUCTION

The knee joint is a stable joint owed to the menisci and ligaments that provide structural stability to the joint. The two fibro-cartilaginous menisci act as shock absorbers and improve knee joint congruency by aligning the femoral and tibial condyles during joint movement. Ligaments such as the extra-capsular (e.g., medial and lateral collateral ligaments) and the intra-articular (e.g., anterior and posterior cruciate ligaments) aid knee function and also stabilize it. Despite its stability, the medial collateral ligament

Corresponding author:
Oladiran I. Olateju. School of Anatomical Sciences, Faculty of Health Sciences, University of the Witwatersrand, 7 York Road, Parktown, 2193, Johannesburg, Republic of South Africa. Phone: +27 11 717 2763; Fax: +27 11 717 2422. E-mail: Oladiran.Olateju@wits.ac.za

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and the anterior cruciate ligament (ACL) are the most injured with the ACL requiring a surgical reconstruction using a graft (Hurley et al., 2018; Lalwani et al., 2020).

The harvested graft must closely match the size and biomechanical strength of the ACL. Factors such as the length of the harvestable graft, location, post-surgery recovery of the donor site must be considered when choosing a graft (Hamada et al., 1998; Shelton and Fagan, 2011; Reboonlap et al., 2012; Janssen et al., 2013; Sun et al., 2020). Grafts come in a variety of options, e.g., synthetic graft, allograft or autograft (Legnani et al., 2010; Macaulay et al., 2012; Hulet et al., 2019). Consequently, the choice of graft often depends on the surgeons' preferences based on their clinical trainings and experiences (Mall et al., 2012). No ideal graft exists for ACL reconstruction, so the search for an optimal graft continues. Each graft has its own advantages and disadvantages and may differ extensively in everyone (Romanini et al., 2010; Cerulli et al., 2013; Dhammi et al., 2015). From an anatomical point of view, there are morphological differences amongst individuals of different sexes, race and ethnicity, which means that the choice of graft in an individual may not be solely based on a surgeon's preference (Xerogeanes et al., 2013; van Zyl et al., 2016; Gupta et al., 2017; Vadgaonkar et al., 2018). This study explored the morphometric profile of the QT, a commonly used autograft (Frank et al., 2017), with the aim that it could serve as a guide to surgeons when choosing autografts.

Restoration to the native anatomical footprint is the most important factor in the ACL reconstruction which entails that the graft being 1) biomechanically similar to the ACL; 2) easily harvestable; 3) easily secured surgically and 4) able to have a rapid healing process (Iriuchishima et al., 2013; Dhammi et al., 2015). In addition, the graft size should be customizable to the patient's native ACL morphometry (Hulet et al., 2019). The QT is one of the strongest tendons in the human body situated on the anterior compartment of the thigh, where it serves as a conjoint tendon for the quadriceps femoris muscles (i.e., rectus femoris, vastus intermedius, vastus medialis and vastus lateralis). The QT with its muscles flexes the hip, extends the knee joint and keeps the knee from buckling when standing – an action that enables walking (Ilan et al., 2003; Slone et al., 2015).

The QT has gained popularity for use as a graft because of its favourable biomechanics, low donor-site morbidity, large cross-sectional area, predictability of healing outcome and ease of harvest (Slone et al., 2015; Heffron et al., 2019). To increase the QT graft effectiveness, the central QT–bone construct is recommended for the ACL reconstruction providing low donor site morbidity, adequate size and high tensile strength (Fulkerson and Langeland, 1995; Harris et al., 1997; Stäubli et al., 1999; DeAngelis and Fulkerson, 2007; Geib et al., 2009; Slone et al., 2015; Shani et al., 2016). The QT is considerably thick and wide and provides abundant harvestable tissue (Fulkerson and Langeland, 1995) but little information on the extent of the harvestable tendon area exists in the literature. Thus, this study presents data on the morphometric profiles (i.e., the surface area, length and widths) of the harvestable area of the QT using a simple tracing method. Correlation of paired parameters was also performed to reveal any relationship. It is envisaged that this study will shed more light, and create an awareness on, the suitability and usability of the QT graft in individuals. Knowledge of this may further strengthen its popularity as an autograft.

MATERIALS AND METHODS

Demographic of samples

Lower limbs of adult formalin–fixed cadavers of South Africans of European ancestry were used in the study. This study assumed a mean of 73.5 mm (standard deviation = 12.3 mm) for females and a mean of 81.1 mm (standard deviation = 10.6 mm) for males for the length of the QT (measured from the musculotendinous junction of rectus femoris to the superior aspect of patella) (Xerogeanes et al., 2013) to determine the sample size required for the present study. At 80% statistical power and a significance level of 5%, the minimum sample size required was 74 cadavers (i.e., 37 cadavers per sex). Consequently, the final sample size was 40 female (79 lower limbs assessed) and 39 male cadavers (77 lower limbs assessed). The QT in both limbs of each cadaver was measured, and any cadaver limb with obvious physical scars or deformities was excluded from the study. The cadavers were housed in the School of Anatomical Sciences at the University of the Witwatersrand, Johannesburg, South Africa for teaching purposes. This study was performed in line with the principles of the Declaration of Helsinki. Waiver was granted by the Human Research Ethics Committee (Medical) of the University of the Witwatersrand (Ethics Waiver Number: W-CJ-140604-1). The mean age of the male cadavers was 76.2 years (range: 53 – 96 years) while that of the female cadavers was 75.3 years (range: 46 – 96 years).

Dissections

To expose the QT, the cadaver was placed in a supine position with the lower limbs fully extended. For the dissection (by S.L. and O.I.O. – anatomists with experiences in human morphometry), a longitudinal incision on the anterior surface of the lower limb was made extending from midway of the thigh to midway of the leg and passing through the centre of the patella. Transverse incisions perpendicular to the longitudinal incision were made at the proximal end, at the level of the patella and at the distal end to expose the region of interest and to allow for adequate space for observation and morphometric measurements. Subsequently, the skin, subcutaneous fascia, fat, fascia lata, and crural fascia were carefully removed without altering the QT morphology.

Morphometry of QT

For the QT morphometry (by S.L. and O.I.O.), the knee was flexed at an angle of about 45° and then the QT was carefully wiped with a dry absorbent cloth. A non-elastic transparent wax paper (dimension: 5 cm x 5 cm x 19 μm; superior wax paper – donated by Superhaze Trading Company, Tongaat, South Africa) was then carefully placed so that it assumed the curvatures of the underlying QT (Fig. 1). The wax paper on the tendon was firmly secured with pins. Subsequently, a permanent marker was used in order to trace out the margins of the tendon onto the wax paper. To further enhance visibility and accuracy of the tracing, the margins of the tendon were pre-marked with a permanent marker before placing the wax paper onto the QT.

The wax paper was removed after the tracing and a known scale bar was drawn on it. The wax paper with its inscribed scale bar was then scanned at 300 dpi using an Epson workforce DS-50000 scanner. From the digitized image, the surface area (SA), straight distal width (SDW), curved distal width (CDW) and length of tendon (LOT) for the QT were measured from the digitized image using an ImageJ 1.47v software (NIH, USA). Each parameter was measured twice and the average of the two measurements was used for the analyses. The parameters for the QT are described in Table 1. In order to normalize the data, the length of each lower limb at full extension from the anterior superior iliac spine to the medial malleolus was also measured using a measuring tape (Sabharwal and Kumar, 2008; Gupta et al., 2017). The raw data of the measurements were normalized by

Table 1. Parameters for the quadriceps tendon.

Parameter	Acronym	Description
Surface area	SA	Area of tendon which is defined by the margins of the tendon i.e. infero-medial border – vastus medius; infero-lateral border – vastus lateralis; inferior border – tendon attachment on the base (superior border) of patella using the medial and lateral borders of the patella as the landmarks
Straight distal width	SDW	Measurement taken as 'a crow flies' at the inferior border of QT using the medial and lateral borders of the patella as landmarks
Curved distal width	CDW	Measurement taken along the curvature of the inferior border of QT using the medial and lateral borders of the patella as landmarks
Length of tendon	LOT	Maximum height from the highest peak at the musculotendinosus junction of QT to the half-way of the CDW at the inferior border of the tendon

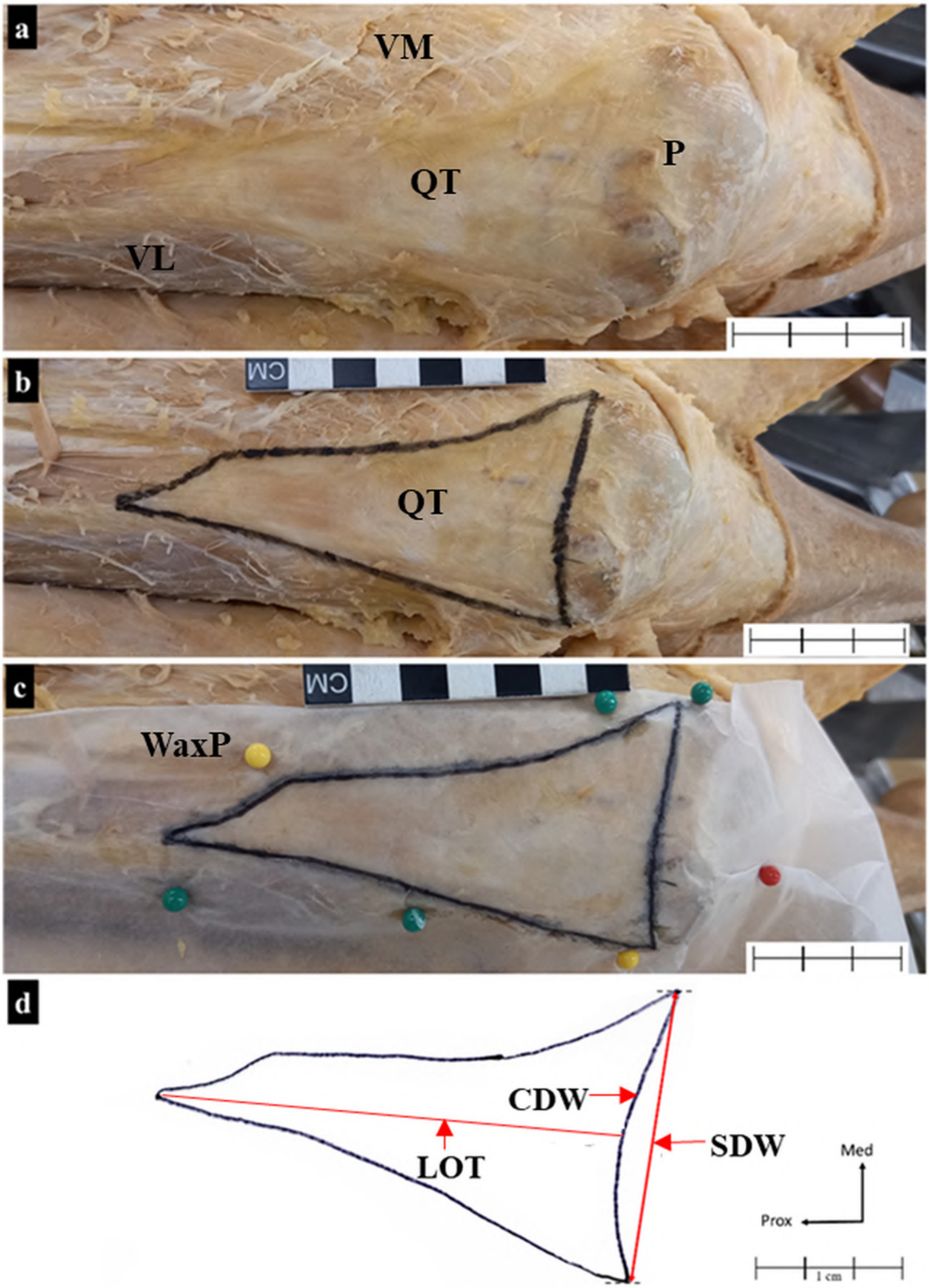

Fig. 1.- Illustrations of the QT tracings on the anterior compartment of the thigh showing (**a**) the exposed QT after removing the superficial structures, (**b**) the highlighted QT margins (i.e. its extent) with a permanent marker in order to improve visibility and tracing accuracy, (**c**) the QT tracing on a superimposed wax paper secured by coloured pins to assume the curvature of QT and (**d**) the digitized image of the traced tendon on the wax paper from which parameters were measured. VM – Vastus medialis, VL – Vastus lateralis, P – patella, QT – Quadriceps tendon, WaxP – Wax paper, LOT – length of tendon, CDW – curved distal width, SDW – straight distal width, Prox – proximal; Med – medial.

dividing the obtained values of the SA, SDW, CDW and LOT by the corresponding lower limb length (LLL).

Statistical analyses

An intra-observer reliability test was conducted (by S.L) at the beginning of the data collection where two independent sets of measurements were taken from the same cadavers at two weeks apart. A Lin's Concordance test (ρc) was performed to determine the level of precision and accuracy between the test and retest measurements. Data collection was then carried out after the reliability test revealed that the level of agreement was substantial (i.e. ρc > 0.95) (Landis and Koch, 1977; McBride, 2005). To test for normality, a Shapiro-Wilk test was carried out for each measurement. All the normalized data were not normally distributed thus a Mann-Whitney U test was used for sex or side comparison. To determine a possible correlation between any two paired parameters, a Pearson's correlation was used for normally distributed raw data, while a Spearman's correlation was used for not normally distributed raw data. All statistical analyses were performed using a SPSS software (version 22.0; IBM, US). Statistical difference of 5% was regarded as significant for all the statistical analyses.

RESULTS

Test of reliability of measurements

The ρc values for the measurements of the QT are shown in Table 2. The ρc values ranged from 0.969 for SA to 0.999 for LOT. Based on these results, all the measurements of the QT are considered to have an error low enough to be acceptable.

Table 2. Lin's concordance correlation of reproducibility for the measurements of the quadriceps tendon.

Parameter	ρc
SA	0.969
LOT	0.999
SDW	0.995
CDW	0.989
LLL	0.997

SA – surface area; LOT – length of tendon; SDW – straight distal width; CDW – curved distal width; LLL – length of lower limb

Morphometry of the lower limb

To reiterate, the measurements for the QT in each cadaver were normalized using the corresponding LLL. There was no significant side difference ($p > 0.05$) in the LLL in both sexes (Table 3). In both limbs, the mean LLL of the male cadavers was significantly higher than the mean LLL of the female cadavers ($p < 0.05$).

Morphometry of the quadriceps tendon

The descriptive analyses of the data for each side and according to sex for the QT are shown in Table 4. For all the measurements from the female or the male cadavers, there was no statistically significant difference in sides (i.e. left vs right). Similarly, no significant difference was obtained when the measurements in the female cadavers were compared with the male cadavers except for the SDW of the male left limb which was significantly higher than the female left limb ($p = 0.033$). Despite the non-significant difference between the measurements from both limbs, the SA measure of one limb was different from the other limb in most of the individual cadavers assessed (Fig. 2). This is an indication that the surface area of the QT in both limbs are morphometrically different in some individuals compared to the similarity of the measurements for the LLL (for illustrative purposes) in both limbs of the same cadaver (Fig. 2).

Correlation analyses on the measurements of the quadriceps tendon

The correlations between any paired QT dimensions showing a clear detail about the strength of their relationships are shown in Table 5. Only paired measurements that revealed moderate (range 0.4-0.69) or strong correlations (range 0.7-1.0) (Schober et al., 2018) are presented. Using the Pearson's or Spearman's correlation (R), strong correlations were observed between the paired measurements of SDW and CDW ($R \geq 0.7$) in both limbs of the female and the male cadavers. A strong correlation was also observed between SA and LOT ($R \geq 0.7$) except for the left lower limb in the female that showed a moderate correlation ($R \geq 0.6$). In addition, the relationship of the LLL (male or female) with each measurement was

Table 3. Comparison between the measurements of the left and the right lower limb lengths.

	Left			Right			
	Number of limbs assessed	Mean (median) (mm)	SD	Number of limbs assessed	Mean (median) (mm)	SD	p
Female	40	860.6* (857.5)	50.21	39	860.846* (865.0)	48.39	0.979
Male	39	926.7* (925.0)	35.88	38	927.474* (920.5)	38.06	0.926

*Significant difference p = 0.0000 (M > F). SD – standard deviation

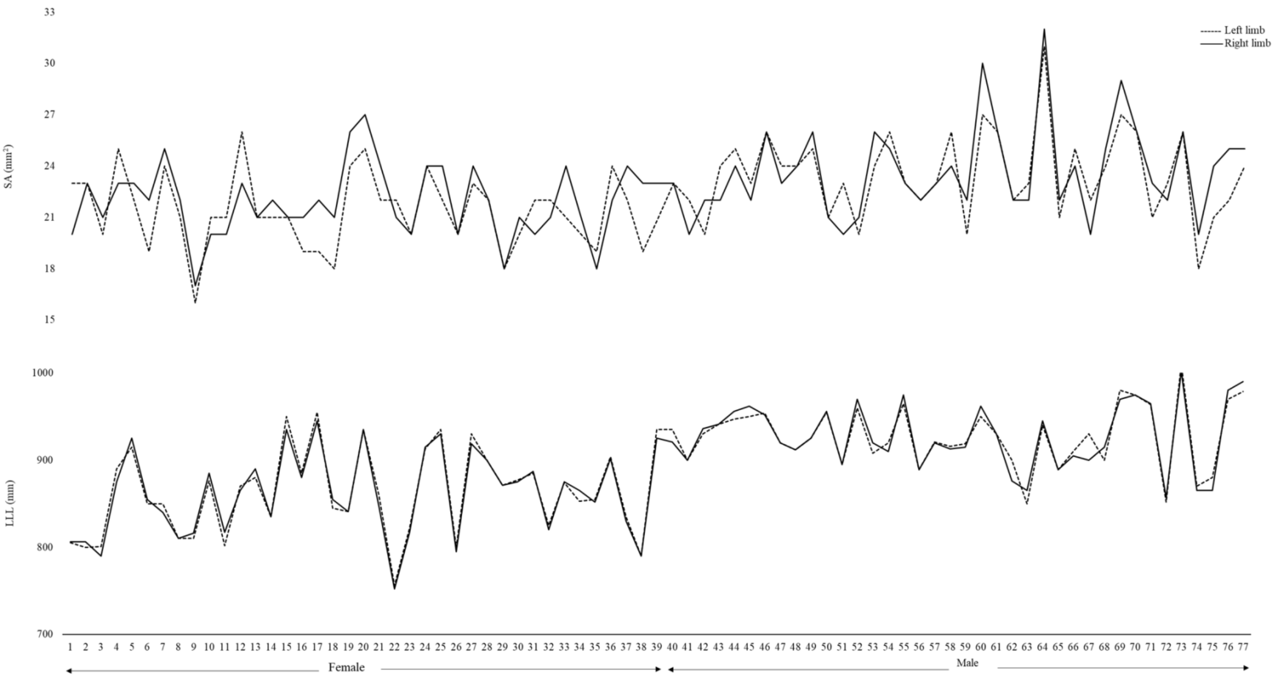

Fig. 2.- Line graphs showing patterns of variation in SA of QT or LLL of both limbs for each individual cadaver. The measurement of SA of one limb is visibly different from the other limb in the cadavers assessed compared to the measurements of LLL in both limbs that are visibly similar.

determined. Only moderate correlation was observed in the paired parameters of LLL vs SA or LLL vs CDW for the male right limb.

DISCUSSION

In the event of an ACL injury, repair of the ligament is necessary to restore the anatomical and functional biomechanics of the damaged ligament (Macaulay et al., 2012). Poor management or treatment plan will lead to unbearable pain, knee function impairment, deterioration of the surrounding cartilage as well as increasing the chances of developing osteoarthritis (Øiestad et al., 2010; Hijazi et al., 2015; Shultz, 2015; Sayampanathan et al., 2017). Surgical repair using an autograft sourced from the patient is the commonly used approach for ACL reconstruction. Various tendons can be used as an autograft however the preference for an autograft often depends on the clinical training and experience of the surgeon.

Generally, human height is a useful parameter for stature in anthropometry and morphometry studies (Xerogeanes et al., 2013; Gupta et al., 2017; Krebs et al., 2019). However, when the height of the subject cannot be accurately measured as in the case of cadavers due to post-mortem variation in body sizes (Cardoso et al., 2016; Ferorelli et al., 2017), the lower limb is often used to indicate stature (Treme et al., 2008; Chiang et al., 2012;

Table 4. Comparison of the measurements of the left and right quadriceps tendon.

	Left					Right					
		Raw		Normalized			Raw		Normalized		
	Number of limbs assessed	Mean (mm)	Mean (mm^2)	Mean	SD	Number of limbs assessed	Mean (mm)	Mean (mm^2)	Mean	SD	p
Female											
SA	40		21.23	0.025	0.003	39		21.90	0.025	0.002	0.440
LOT	40	78.77		0.092	0.016	39	84.75		0.099	0.014	0.052
SDW	40	49.96		0.058*	0.007	39	51.58		0.060	0.008	0.735
CDW	40	53.18		0.062	0.008	39	54.75		0.064	0.008	0.344
Male											
SA	39		23.44	0.025	0.003	38		23.74	0.026	0.003	0.421
LOT	39	86.51		0.093	0.013	38	91.23		0.098	0.013	0.104
SDW	39	57.24		0.062*	0.006	38	56.15		0.061	0.006	0.544
CDW	39	60.74		0.066	0.006	38	60.63		0.065	0.007	0.442

*Significant difference p = 0.033 (M > F). SA_{QT} – surface area; LOT_{QT} – length of tendon; SDW_{QT} – straight distal width; CDW_{QT} – curved distal width; SD – standard deviation

Table 5. Correlation coefficient between measurements of the left and right quadriceps tendon.

	Female				Male			
	SA	LOT	SDW	CDW	SA	LOT	SDW	CDW
Left								
SA		0.6*				0.7*	0.4***	
LOT								
SDW				1.0*				
CDW							0.9*	
LLL								
Right								
SA		0.7*		0.4**		0.8*		0.4**
LOT								
SDW	0.5**			1.0*				
CDW							0.8*	
LLL					0.5**			0.4***

*p < 0.0001. **p < 0.01. ***p < 0.05 . SA – surface area; LOT – length of tendon; SDW – straight distal width; CDW – curved distal width; LLL – length of lower limb

Sundararajan et al., 2016; Mohd Asihin et al., 2018; Sakti et al., 2019; Dziedzic et al., 2020). Even though the LLL parameter used in the present study is consistent with the previous studies, the focus of this study was not to determine stature in this population group. Instead, LLL was used to normalize the measurements and to determine the relationships between the LLL and other measurements. On another note, limb length was significantly higher in the male cadavers than in the female cadavers, which is consistent with previous reports that measured limb length in different population groups: e.g., an American population (Treme et al., 2008), a Chinese population (Chiang et al., 2012) and a South Sulawesi population (Sakti et al., 2019).

In morphometric studies of structures (e.g., tendons or ligaments in the lower limb), some measurements may indicate a leg dominance when a measurement on one limb is significantly different from a similar measurement of the other limb: e.g., in semitendinosus tendon (Pichler et al., 2008; Bundi et al., 2016) and patellar ligament (Olateju et al., 2013). Factors such as age, sex, lifestyle and activity level of an individual may contribute to leg dominance as well as tendon pathology arising from injuries (Latiff et al., 2021). In a study by Gupta et al. (2017), the limb length of both sides was not significantly different and is consistent with the findings of the present study. This means that leg dominance may not be associated with limb length but may be directly linked to the tendon or ligament morphometries as is the case in Pichler et al. (2008), Olateju et al. (2013) and Bundi et al. (2016). In this study, none of the measurements exhibited a leg dominance as there were no significant differences when the measurements from both limbs were compared. This is also consistent with the cadaveric studies by Hijazi et al. (2015) and Tanpowpong et al. (2019).

The morphometric profile of the QT provides useful information that is beneficial to ACL reconstruction (Lippe et al., 2012). The large harvestable tissue area of the QT is an important feature that makes it a commonly used autograft. Other advantages of the QT is that it can be reliably harvested (Sheean et al., 2018), and that it has a similar ultrastructure to other graft sources: e.g., patellar tendon and hamstrings (Macaulay et al., 2012). This study presents data on the surface area of the QT which have not been collected before. The surface area of the QT was similar in both sexes and in both limbs in the population group assessed. Unfortunately, there is no report in the literature to compare with the present findings, so it is not discussed further. The data on the surface area of the QT may be of benefit to the rate of recovery at the harvest site, since the QT has been shown to have more collagen content (Hadjicostas et al., 2007) which contributes to its tensile strength (Shani et al., 2016; Krebs et al., 2019; Latiff and Olateju, 2022). The implication of this is that the remaining collagen content after the harvesting of a graft should be sufficient for the QT to recover quicker and function more satisfactorily than the patellar tendon, which has a lesser collagen content (Hadjicostas et al., 2007) and a smaller surface area than the QT (unpublished report). It is thus suggested that the surface area of the QT should be considered in pre-operative planning where the QT is being considered as a graft in an individual.

Morphologically, the QT of the population group assessed was similar to a previous study (Lippe et al., 2012). Some cadavers exhibited a dual peak (51%) while others had a single peak (49%). The dual peaks are because the vastus lateralis and vastus medialis become tendons (i.e., the QT) before inserting at the base of the patella (Lippe et al., 2012). Understanding and acknowledging this characteristic feature of the QT is important during harvesting in order to avoid harvesting from the short peak (which is mostly positioned medially) instead from the long peak that provides adequate graft tissue (i.e., the maximum tendon length) for harvesting (Lippe et al., 2012). In this study, the maximum tendon length was taken from the more prominent peak in the case of dual peaks (Lippe et al., 2012; Tanpowpong et al., 2019).

The average maximum tendon length for both limbs in this study was 81.76 mm in the female and 88.87 mm in the male. Due to differences in morphometric approaches and other factors such as age, race and ethnicity (Gupta et al., 2017), other studies report a lower maximum tendon length. Yamasaki et al. (2021) reported a QT length of about 59.5 mm in a MRI study on a Japanese population, while a QT length of 61 mm was reported in cadavers by Harris et al. (1997) and a length of 63 mm in a Thai population by Tanpowpong et al. (2019). However, other studies reported a maximum tendon length within the range observed in the present study. For example, Stäubli et al. (1999) reported an average tendon length of about 86 mm for both limbs, Krebs et al. (2019) reported an average of about 83 mm in a cadaveric study while Thi and Ha (2021) and Lippe et al. (2012) reported averages of about 79 mm and 88 mm respectively. With similarities in the mean QT length, it seems that the in-situ tendon tracing and methodologies used in the present study were adequate. Likewise, the QT length in the present study was not sexually dimorphic despite the observed higher tendon length in the male than in the female. This however contradicts the MRI study by Xerogeanes et al. (2013) that found a significant higher tendon length in males (~81.1 mm) than in females (~73.5 mm). A cadaveric study in a Saudi Arabian population also reported a significantly higher QT length in males (Hijazi et al., 2015).

To give a further detailed morphometry that could be used pre-operatively, the straight and curved distal widths (SDW and CDW) were measured on the tracings. The tendon tracings provided an additional advantage in that the actual/curved widths can be easily measured unlike in radiological records: e.g., MRI. One or both measurements may be adequate for pre-operative investigation and planning when a QT autograft is being considered. The study however did not find a significant difference between the straight and curved distal widths in the population group assessed. In addition, the SDW or the CDW did not reveal a side difference. However, SDW (not the CDW) exhibited a sex dimorphism where the male QT width was wider than the female. This is consistent with the report by Hijazi et al. (2015) despite the narrower widths reported compared to this study. The present study found SDW to be about 50.8 mm in the female and about 56.7 mm in the male (left and right limbs combined), while the QT widths of about 26.7 mm in the female and about 28.5 mm in the male (left and right limbs combined) were reported by Hijazi et al. (2015). Thi and Ha (2021) reported a narrower QT distal width (~ 36.0 mm) as well. On the other hand, Lippe et al. (2012) (~43.3 mm), Krebs et al. (2019) (~44.8 mm) and Tanpowpong et al. (2019) (~46.2 mm) reported QT distal widths in cadavers within the range observed in the present study.

One advantage the QT has over the other commonly used autografts (e.g., semitendinosus and patellar tendons) is that the area of harvestable tissue is high. Harvesting a standard 10–mm wide (Adams et al., 2006; Shelton and Fagan, 2011; Iriuchishima et al., 2013; Hijazi et al., 2015) and a 70–mm long (van Eck et al., 2010) QT tissue for an ACL reconstruction means that there is sufficient tissue that can be harvested and at the same time leave sufficient tissue for tendon functionality and healing at the harvest site. This is also highlighted in other reports (Xerogeanes et al., 2013; Krebs et al., 2019; Yamasaki et al., 2021). Based on the observed morphometries of the tendon length (female: 52.1 – 116.7 mm and male: 67.3 – 121.8 mm) and width (female: 35.8 – 68.9 mm and male: 48 – 70.1 mm) of the QT in the present study, about 8% (i.e., 6 limbs out of 77) of the male limbs and about 17% (i.e., 13 limbs out of 79) of the female limbs fall short of the required dimensions of a QT autograft, and thus these individuals may not qualify for an ACL reconstruction using the QT autograft. Interestingly, these observations were found bilaterally in 3 cadavers (i.e., 1 male and 2 females). This means that the QT would not be suitable as an autograft in these individuals if they were to undergo an ACL reconstruction. In comparison to Tanpowpong et al. (2019), about 61% of the Thai population group assessed were considered not suitable for a QT autograft due to their short QT length. In these individuals, a bone–patellar tendon–bone autograft could be an alternative (Yamasaki et al., 2021). Predicting the size of the autograft for use in surgery may be a difficult task (Krebs et al., 2019) but this is where morphometric studies have become useful (Helito et al., 2015; Zakko et al., 2017).

It may be possible that the QT of one limb may be adequate but not the other limb. Depending on the strategies or plans of the surgeon, the QT may be harvested from the limb with a damaged ACL or from the undamaged limb (Shelbourne and Urch, 2000; von Essen et al., 2021). However, there is a need for caution as there are individuals with observable differences in the morphometry of the QT of both limbs. For these individuals and depending on which leg is injured, the surgeon must be cautious in choosing which graft to use. Thus, the preference of the surgeon based on the surgical training and experience may not be applicable but rather by an informed decision provided by tendon morphometry. It is not advisable to harvest a graft from an injured limb, as there is a high risk of compounding the problem in this limb. In the event of harvesting a graft from the contralateral limb, as explained by Shelbourne and Urch (2000), the trauma of the surgery is divided between the limbs, and this allows the patient to focus on the rehabilitation process for each limb. For the recovery of both knees and the return of knee functions, patients may not have to worry about a major loss of strength in the limb where the ACL was reconstructed as the graft was harvested from the non-injured limb. Even though a non-injured limb is being 'disturbed', this proves to be advantageous for recovery of both limbs (Shelbourne and Urch, 2000).

In the present study, correlation between paired parameters of the QT was tested to determine the relationship between them. A strong correlation was found between the distal width (i.e., straight and curved) in both limbs and for both sexes. A strong correlation was also found between the SA and LOT (except for the female left limb that was moderate). This relationship is another important factor to consider during pre-operative investigation of the QT. Correlation was also extended to determine the relationship between the LLL and other QT measurements. It is important to note that the height of a subject and the length of limb in the same subject may not be directly related. Interestingly, none of the parameters paired with the LLL showed a strong correlation unlike in previous reports by Xerogeanes et al. (2013) and Krebs et al. (2019) that found a strong correlation between the height of individual and the tendon length.

In conclusion, the cadaveric approach used in this study is considered reliable and reproducible, evident by the results of the test of reliability. It is true that a cadaveric approach has many limitations, e.g., sample size, tissue shrinkage, population representation, etc., but it provides a 3–dimensional structure from which several measurements can be obtained *in situ* (Olateju et al., 2013). The QT provides an abundant harvestable tissue which is superior to other tendons (e.g., patellar or semitendinosus tendon), but surgeons must be cautious as the QT in some individuals may not be adequate as an autograft. When it comes to faster healing and integration of graft, the benefits of the bone–patellar tendon–bone autograft cannot be matched by the QT. This makes the patellar tendon a popular graft choice, especially when a faster return to activity level is desired. However, a bone–patellar tendon–bone autograft may be inadequate in a surgical approach, like in an all-inside ACL reconstruction, where it becomes difficult to appropriately shorten the graft length (Slone et al., 2016). In a procedure like this, a QT graft is preferred because of its large harvestable area and accessibility. The discussed morphometric data of the QT will contribute to knowledge and will be beneficial for pre-operative planning for ACL reconstruction.

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Author contributions

S.L.: Data collection, Data analyses, Manuscript editing.

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