Eur Radiol (2015) 25:290–298
DOI 10.1007/s00330-014-3424-2

MUSCULOSKELETAL

Cross-sectional area measurements versus volumetric assessment of the quadriceps femoris muscle in patients with anterior cruciate ligament reconstructions

Magda Marcon · Bernhard Ciritsis · Christoph Laux · Daniel Nanz · Thi Dan Linh Nguyen-Kim · Michael A. Fischer · Gustav Andreisek · Erika J. Ulbrich

Received: 26 May 2014 / Revised: 15 July 2014 / Accepted: 29 August 2014 / Published online: 31 October 2014

Abstract

Objective Our aim was to validate the use of cross-sectional area (CSA) measurements at multiple quadriceps muscle levels for estimating the total muscle volume (TMV), and to define the best correlating measurement level.

Methods Prospective institutional review board (IRB)-approved study with written informed patient consent. Thighs of thirty-four consecutive patients with ACL-reconstructions (men, 22; women, 12) were imaged at 1.5-T using three-dimensional (3D) spoiled dual gradient-echo sequences. CSA was measured at three levels: 15, 20, and 25 cm above the knee joint line. TMV was determined using dedicated volumetry software with semiautomatic segmentation. Pearson's correlation and regression analysis (including standard error of the estimate, SEE) was used to compare CSA and TMV.

Results The mean±standard deviation (SD) for the CSA was 60.6±12.8 cm^2 (range, 35.6–93.4 cm^2), 71.1±15.1 cm^2 (range, 42.5–108.9 cm^2) and 74.2±17.1 cm^2 (range, 40.9–115.9 cm^2) for CSA-15, CSA-20 and CSA-25, respectively. The mean±SD quadriceps' TMV was 1949±533.7 cm^3 (range, 964.0–3283.0 cm^3). Pearson correlation coefficient was $r=0.835$ ($p<0.01$), $r=0.906$ ($p<0.01$), and $r=0.956$ ($p<0.01$) for CSA-15, CSA-20 and CSA-25, respectively. Corresponding SEE, expressed as percentage of the TMV, were 15.2 %, 11.6 % and 8.1 %, respectively.

Conclusion The best correlation coefficient between quadriceps CSA and TMV was found for CSA-25, but its clinical application to estimate the TMV is limited by a relatively large SEE.

Key points

- *Cross-sectional area was used to estimate QFM size in patients with ACL-reconstruction*
- *A high correlation coefficient exists between quadriceps CSA and volume*
- *Best correlation was seen 25 cm above the knee joint line*
- *A relatively large standard error of the estimate limits CSA application*

Keywords Knee injuries · Quadriceps muscle · Anterior cruciate ligament reconstruction · Magnetic resonance imaging · Three dimensional imaging

---

M. Marcon · D. Nanz · T. D. L. Nguyen-Kim · M. A. Fischer · G. Andreisek · E. J. Ulbrich (✉)
Department of Radiology, University Hospital Zurich, Ramistrasse 100, 8091 Zurich, Switzerland
e-mail: Erika.Ulbrich@usz.ch

M. Marcon
e-mail: magda.marcon@gmail.com

D. Nanz
e-mail: Daniel.Nanz@usz.ch

T. D. L. Nguyen-Kim
e-mail: thidanlinh.nguyen@usz.ch

M. A. Fischer
e-mail: MichaelAlexander.Fischer@usz.ch

G. Andreisek
e-mail: gustav@andreisek.de

M. Marcon
Department of Radiology, University Hospital Udine, P.le S. Maria della Misericordia, 33100 Udine, Italy

B. Ciritsis · C. Laux
Department of Traumatology, University Hospital Zurich, Ramistrasse 100, 8091 Zurich, Switzerland

B. Ciritsis
e-mail: Bernhard.Ciritsis@usz.ch

C. Laux
e-mail: Christoph.Laux@usz.ch

Abbreviations

CSA	Cross-sectional area
TMV	Total muscle volume
ACL	Anterior cruciate ligament
QFM	Quadriceps femoris muscle

Introduction

Quadriceps femoris muscle (QFM) insufficiency is a common complication following anterior cruciate ligament reconstruction, and it is at least partially attributed to quadriceps atrophy [1, 2]. The QFM atrophy is correlated to the QFM strength and the size of the QFM represents an important clinical indicator in the outcome assessment after rehabilitation programs [2–8].

Estimation of QFM atrophy in the clinical setting have usually involved girth measurements with a tape, but it also involves other thigh muscles, as well as bone and subcutaneous fat; despite discordant results, this method is described as a reliable tool in the assessment of QFM when no isokinetic strength testing is available [9, 10].

The use of ultrasound muscle thickness measurements to estimate the TMV has also been investigated, but this method is limited by a high standard error of the estimate [11, 12]. Computer tomography (CT) and magnetic resonance (MR) imaging are considered the modalities of choice for the estimation of the QFM size [13–16]. MR imaging is often preferred, as no ionizing radiation is involved. Usually, the total muscle volume (TMV) is determined by manual segmentation of the QFM on multiple contiguous axial anatomical MR images by outlining of the muscles 'margins.' Dedicated software is then used to calculate the cross-sectional area (CSA) of the QFM, and ultimately the TMV by the multiplication of the individual CSAs with the image slice thickness. Computerized semi-automated or fully automated segmentation methods [17], as well as other procedures such as the truncated cone formula and third-order polynomial regression [18–20], have been developed, but are either not precise or time efficient enough to allow their routine clinical use [15, 20, 21].

Therefore, assessment of a single axial anatomical CSA is often employed as a faster method to obtain a quantitative muscle parameter [4, 22–24]. An additional advantage related to the use of a single CSA measurement is the demonstrated excellent intra-observer and inter-observer reliability, which suggests that CSA measurements could be a reliable and simple tool for daily routine use [24, 25]. Nevertheless, previous studies indicate that a single CSA measurement may not necessarily be representative of the total QFM volume [20] and the optimal level of CSA measurement along the muscle's length has also not yet been defined [19, 21, 26]. For example, Strandberg et al. [27] used a single slice 15 cm above the knee joint, whereas Callaghan et al. [10] used a single slice at the thigh mid-point between the lateral joint line of the knee and the great trochanter as reference to estimate the muscle size. To the best of our knowledge, the accuracy of QFM CSA measurements at different levels above the knee joint line compared to the TMV was not investigated before. Therefore, it remains unclear if time-consuming muscle volumetry procedures can be replaced by more time-efficient CSA measurement methods in clinical practice.

The purpose of our study was to measure CSAs of the QFM at multiple locations, and to define the best correlating measurement level to estimate the TMV derived by QFM volumetry. All measurements were performed in a cohort of patients with ACL reconstructions.

Materials and methods

Study subjects

This was a prospective study with institutional review board approval and written informed consent from all study subjects. The study was Health Insurance Portability and Accountability Act (HIPAA) compliant and none of the authors had a financial interest. Some study subjects or cohorts have been included in another substudy [28] focusing on the vastus medialis muscle atrophy in patients after ACL reconstruction. However, the study aim significantly differed from the previously mentioned study and no data or portions of data presented in this present study have been, or will be, published elsewhere.

A total of 34 patients with ACL reconstructions [women, 12; mean±standard deviation (SD) age, 31.3±8.8 years (range, 20.0–52.0 years); men, 22; mean±SD age, 30.9±6.5 years (range, 21.0–51.0 years)] underwent MR imaging between March and August 2013. Mean time interval±SD between knee injury and surgery was 18.3±30.8 weeks (range, 0.0–156.0 weeks). The mean time interval±SD between surgery and follow-up MR examination was 19.7±3.6 months (range, 13–24 months).

Inclusion criteria were: (*a*) history of knee trauma with ACL tear; (*b*) Bone-Patellar Tendon-Bone (BPTB) reconstruction; (*c*) no additional ligament injury at time of trauma; (*d*) completed rehabilitation program, asymptomatic and with functional recovery [defined as a Knee and Osteoarthritis Outcome score (**KOOS**) above 91 for activity of daily living and above 80 for sport and recreation function [29, 30], evaluated during a follow-up examination performed by two orthopedic surgeons (BC, CL) at our institution]; (*e*) normal range of motion (extension within 2° and flexion within 5° of the non-operated knee according to International Knee Documentation Committee (IKDC) criteria [31], stable knee and normal muscle strength. Exclusion criteria were: (*a*) contraindication to MR imaging; (*b*) complex knee injuries with

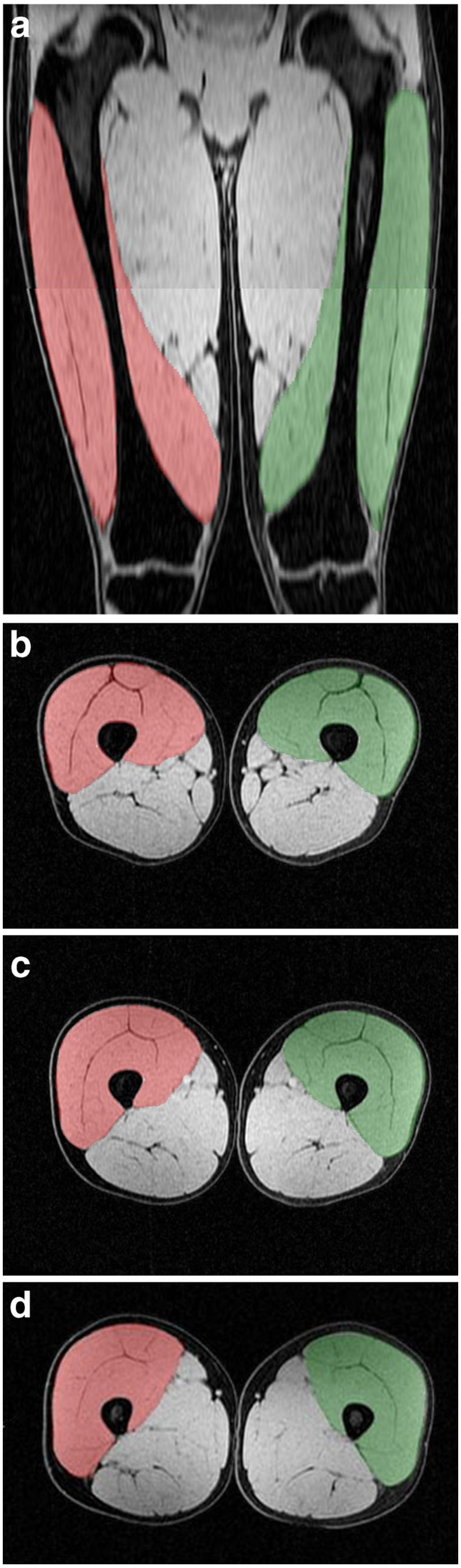

Fig. 1 Series of water signal-only MR images in a patient with left ACL ▶ reconstruction. (*A*) Coronal reconstruction shows the three levels of measurement, namely at 15, 20 and 25 cm above the knee joint. (*B–D*) Representative axial images illustrate the cross sectional area measurement at these three levels: CSA-15 (*B*), CSA-20 (*C*) and CSA-25 (*D*)

additional ligament tears; (*c*) systemic disease; (*d*) previous surgery of the lower extremity or hip; (*e*) side-to-side differences in leg length; and (*f*) scoliosis.

MR examination

MR imaging of the thighs was performed using a 1.5-T MR unit (Signa Echospeed EXCITE HDxt; GE Healthcare, Waukesha, Wis) and a twelve-channel body array (HD Body array; GE Healthcare). An axial T1-weighted fast spin-echo (FSE) MR sequence (TR/TE, 551/13 msec; echo train length (ETL), 3-4; section thickness, 6 mm; matrix, 320 × 224) and a three-dimensional (3D) spoiled dual gradient-echo MR sequence (TR/TE, 6.14/2.1,4.2 msec; section thickness, 6 mm; matrix, 320 × 224) were acquired. The latter sequence sampled two echoes, with an excitation flip angle of 5°, and automatically reconstructed pure fat signal-only and water signal-only image series [32]. The water signal-only images provide excellent visibility of the muscles 'margins and were thus used for manual muscle segmentation. The field-of-view covered both thighs from the pelvic girdle to approximately 5 cm below the knee joint. Due to MR scanner restrictions, the left and the right thigh had to be acquired in two different volumes using a cranio-caudal direction (Fig. 1). Subjects were imaged in supine position.

Image analysis

Image analysis was performed by a musculoskeletal radiology fellow (MM) using dedicated software (Myrian1; Intrasense, Paris, France). The software provided tools for measuring distances, areas and volumes. The volumetry tool featured semi-automatic segmentation with linear interpolation and allowed for manual correction of the segmentation process, if necessary.

Image analysis included determination of the femur length, of the CSA of the quadriceps muscle at three levels, and of the TMV. Femur length was defined as the distance from the most proximal portion of the greater trochanter to the most distal portion of the lateral condyle. The CSA of the quadriceps muscle was measured 15, 20, and 25 cm above the knee joint using free-hand drawn regions-of-interests (ROIs). The three levels were referred to as CSA-15, CSA-20, and CSA-25, respectively. Quadriceps volumetry included calculation of the quadriceps TMV also using free-hand-drawn ROIs tracked along the margins of the quadriceps muscles. ROIs were drawn on the most proximal and the most distal slices, where the quadriceps muscles were visible, and on every third slice in between these start-and end-point slices. The decision to use every third slice was based on the minimum number of slices, which the software needed as input data to be able to trace the muscle margins and to calculate the muscle volume. Care was taken to include the whole muscle, to exclude the surrounding fat or connective tissue and to avoid partial volume artefacts. The software's output data included the quadriceps TMV, as well as three-dimensional (3D) reconstructions of the muscle, which in this paper were only used for illustration purposes (Fig. 1).

Image analyses were performed in both legs, the operated and the non-operated side, respectively. For evaluating the intra-observer reliability, the same reader repeated the CSA-15 measurement and the volumetric analysis in 12 of 34 (35 %) patients. There was a minimum of 6 weeks between the two image analysis sessions.

Statistical analysis

Descriptive statistics were performed. Data were reviewed and tested for normal distribution using the Shapiro-Wilk test.

The intra-class correlation coefficient [33] was calculated to evaluate the intra-observer reliability within the repeated CSA-15 and muscle volume measurements. According to Kundel and Polansky [34] and Landis and Koch [35], an ICC greater than 0.80 was considered to be indicative of "almost perfect" agreement (ICC = 1.00, "perfect" agreement).

To evaluate the association between the cross sectional area measurements (CSA-15, CSA-20 and CSA-25) and the TMV, Pearson correlation analysis and a univariate regression analysis (with 95 % confidence interval and Standard Error of the Estimate, SEE) were performed. The SEE was additionally put in relation to the mean TMV and expressed as the percentage of the total QFM volume (SEE_{TMV}) at the three levels to give a relative indication of the SEE. Analysis was performed for each leg separately and for both legs together.

In addition, the paired Student *t* test for related samples was used to test for significant differences between operated versus non-operated leg with regard to the TMV, CSA-15, CSA-20, and CSA-25.

Side-to-side differences were considered statistically significant using a *p* value of less than 0.012 (Bonferroni correction was applied to correct for multiple comparisons; significance level of $\alpha=0.05/4$). For all other analysis, differences with *p* values less than 0.05 were considered statistically significant. All statistical analyses were performed with commercially available software (SPSS, release 17.0; SPSS, Chicago, Ill).

Results

Intra-observer reliability

The intra-observer reliability for the CSA-15 measurements was 'perfect' with an ICC of 1.00 (95 % confidence interval 1.00 to 1.00) and was 'almost perfect' with an ICC of 0.90 (95 % confidence interval, 0.78 to 0.95) for the quadriceps TMV.

Quadriceps CSA

The mean overall CSA-15±SD was 60.6 cm^2±12.8 (range, 35.6–93.4 cm^2). The mean CSA-15±SD was 57.7 cm^2±12.4 (range, 36.0–87.0 cm^2) in the operated leg and 63.5±12.7 (range, 35.6–93.4 cm^2) in the non-operated leg. The mean overall CSA-20±SD was 71.1 cm^2±15.1 (range, 42.5–108.9 cm^2). The mean CSA-20±SD was 67.7 cm^2±14.8 (range, 42.5–100.0 cm^2) in the operated leg and 74.4±14.9 (range, 42.9–108.9 cm^2) in the non-operated leg. The mean overall CSA-25±SD was 74.2 cm^2±17.1 (range, 40.9–115.9 cm^2). The mean CSA-25±SD was 71.1 cm^2±17.0 (range, 40.9–108.6 cm^2) in the operated leg and 77.3±16.9 (range, 46.5–115.9 cm^2) in the non-operated leg (Table 1).

The CSA difference was statistically significant between operated and non-operated legs for all the three levels (all, $p<0.001$). Considering the total femur length as 100 %, the three levels (CSA-15, CSA-20, and CSA-25) corresponded to 34.6±2.4 % (mean±SD; range 30.6–40.5), 46.2±3.2 % (range, 40.8–54.0) and 57.7±4.1 % (range, 51.0–67.5) of the total femur length, respectively.

Muscle volume

The mean overall quadriceps TMV±SD was 1949 cm^3±533.7 (range, 964.0—3283.0 cm^3). The mean quadriceps TMV±SD was 1863.7 cm^3±517.6 (range, 964.0–2967.0 cm^3) in the operated leg and 2034.2 cm^3±543.5 (range, 1138.0–3283.0 cm^3) in the non-operated leg. The side-to-side difference was statistically significant ($p<0.001$) (Table 1).

Correlation between total muscle volume and CSA

A good to excellent linear relationship was found between the cross-sectional areas CSA-15, CSA-20 and CSA-25 and the quadriceps TMV with a Pearson correlation coefficient of $r=0.835$ ($p<0.01$), $r=0.906$ ($p<0.01$) and $r=0.956$ ($p<0.01$), respectively (Table 2, Fig. 2A–C). Similar values were found when the correlation coefficient was calculated for both legs separately (Table 2). The SEE were±295.9 cm^3 for the overall CSA-15, ± 227.9 for the overall CSA-20 and±158.6 for the overall CSA-25, corresponding to a relative SEE_{TMV} of 15.2 %, 11.6 % and 8.1 %, respectively (Table 2).

Table 1 Femur length, quadriceps TMV and CSA-15, CSA-20 and CSA-25

Pt.		Operated Leg				Non-operated Leg			
	FL [cm]	TMV [cm^3]	CSA-15 [cm^2]	CSA-20 [cm^2]	CSA-25 [cm^2]	TMV [cm^3]	CSA-15 [cm^2]	CSA-20 [cm^2]	CSA-25 [cm^2]
1*	48	2710	58.1	75.7	93.6	2706	56.9	71.9	89.6
2*	40	1422	54.0	61.0	58.3	1475	55.4	63.4	62.7
3*	40	1870	62.8	67.2	70.6	2152	71.9	82.4	83.0
4*	45	2153	57.6	72.4	84.2	2455	69.7	86.1	91.0
5*	46	2343	65.4	75.3	80.9	2369	67.4	76.4	84.1
6*	40	1965	67.5	82.8	85.9	2080	70.7	84.2	90.1
7*	46	1935	45.5	63.2	75.4	2487	60.0	81.7	92.6
8*	45	2967	81.3	100.0	108.6	3283	85.2	108.9	115.9
9*	43	2042	68.1	75.6	73.7	1976	62.3	73.1	71.1
10*	42	1552	52.3	61.7	60.8	1799	60.7	66.9	68.6
11*	45	2192	60.9	75.6	80.1	2309	63.8	81.4	86.9
12*	48	2496	70.8	80.4	86.8	2707	71.0	85.6	90.1
13	42	2019	67.4	75.7	82.2	1973	68.0	75.9	78.8
14	37	1476	58.2	62.8	54.9	1560	59.4	65.5	58.9
15	43	2320	77.1	85.9	85.6	2378	82.8	90.6	88.8
16	40	1447	53.6	60.7	59.1	1902	68.9	76.7	75.0
17	45	2588	72.1	91.9	100.1	2755	73.5	94.4	103.1
18	40	1384	54.7	67.2	66.1	1586	64.2	76.5	76.2
19	38	964	38.5	42.5	40.9	1232	47.3	56.2	53.2
20	43	1298	36.3	49.3	53.9	1416	46.0	56.9	58.2
21	41	1322	49.1	53.5	53.2	1462	54.1	58.4	59.4
22	48	2209	61.1	66.8	71.3	2334	70.9	75.7	76.5
23	45	1237	36.0	46.5	52.3	1186	35.6	44.7	49.7
24	45	2187	59.7	72.5	75.0	2567	73.0	87.7	93.1
25	41	1286	47.3	53.2	53.7	1422	50.4	63.3	59.8
26	46	2317	66.8	83.1	92.9	2436	73.7	88.2	95.9
27	49	2131	56.0	62.4	68.0	2496	71.8	77.0	83.1
28	41	1157	39.9	43.9	48.1	1138	38.6	42.9	47.7
29	44	1693	55.5	62.5	68.5	1794	55.4	65.7	73.5
30	44	2549	87.0	97.3	94.4	2628	93.3	100.9	97.7
31	44	1992	58.9	72.6	78.6	2272	66.6	80.7	86.8
32	47	1494	51.0	61.1	61.9	1582	54.8	66.8	67.8
33	45	1489	51.7	55.2	56.4	1967	67.7	72.5	74.1
34	43	1160	40.5	44.0	42.7	1280	46.1	50.7	46.5
Means±SD	43.5±3.0	1863.7±517.6	57.7±12.4	67.7±14.8	71.1±17.0	2034.2±543.5	63.5±12.7	74.4±14.9	77.3±16.9

*Patients analyzed twice for assessing the intra-observer reliability

Pt =patient; FL = femur length

Discussion

The quadriceps cross-sectional area (CSA) is often used to estimate the quadriceps size, an important clinical indicator for the outcome evaluation in patients after knee surgery, e.g., ACL reconstruction [4, 6, 36–38]. Measuring the CSA of a muscle is relatively easy and fast to perform and its high reproducibility supports its clinical use [20]. In our study, we found a perfect intra-observer agreement with an ICC of 1.00 when CSA measurements were repeated after 6 weeks. This confirms the high reproducibility reported in the literature where inter-class and intra-class correlation values of 0.98–1.00 were shown [25, 27].

In the literature, different approaches were used to assess the quadriceps CSA, and a lack of standardization for these measurements is seen [10, 27]. This specifically applies to the

Table 2 Correlation between CSA-15, CSA-20 and CSA-25 and quadriceps TMV

	CSA-15			CSA-20			CSA-25		
	Tot (N=68)	Op (N=34)	Non-op (N=34)	Tot (N=68)	Op (N=34)	Non-op (N=34)	Tot (N=68)	Op (N=34)	Non op (N=34)
r	0.835	0.839	0.823	0.906	0.906	0.903	0.956	0.954	0.955
r^2	0.697	0.704	0.678	0.820	0.821	0.815	0.913	0.910	0.913
SEE [cm^3]	± 295.9	± 286.2	± 313.3	± 227.9	± 222.5	± 237.7	±158.6	± 157.6	± 162.9
SEE$_{TMV}$ [% of TMV]	15.2	15.3	15.4	11.6	11.9	11.6	8.1	8.4	8.0

r = Pearson correlation coefficient; r^2 = R-square; SEE = Standard Error of the Estimate; SEE$_{TMV}$ = SEE expressed as the percentage of the quadriceps TMV; Tot = overall legs; Op = operated leg; Non-op = non-operated leg

fact at which level the measurements should be performed. Therefore, it would be advantageous if a thumb rule could be applied that the measurement level should always be located at a certain distance from the knee joint. A different approach would consist of defining the CSA level at a relative distance considering the femur length, but this would require the MR image acquisition of the whole thigh length [19]. In our study, we evaluated three different levels, located 15, 20 and 25 cm above the knee joint. We found a good to excellent linear relationship between the quadriceps TMV and the CSA at all the three levels in the overall evaluation and also in the operated and non-operated leg subgroups, but the highest correlation coefficient was found 25 cm above the knee joint (r^2=0.956). Our results indicate that the CSA-25 is the most appropriate of the three evaluated levels and should be used for CSA measurements of the quadriceps muscle. The 25-cm distance above the knee joint corresponded to a percentage distance of the femur length of around 58 % (exact numbers were 57.7±4.1 %, range 51.0–67.5 %). Our findings are in agreement with a previous study conducted by Tracy et al. [20], where a very high correlation coefficient (r^2=0.96) was found between the largest single CSA (defined case by case without establishing a standardized level for all the subjects) and the quadriceps volume. In another study, Morse et al. [19] found correlation coefficients within a similar range when they measured and compared the CSA at 40, 50 and 60 % from the distal end of the femur to the quadriceps volume (r^2 values were 0.84, 0.93, and 0.90 respectively). Overall, CSA measurements in the midst of the thighs correlated better with the muscle volume than measurements at the proximal or distal end of the femur. In the study by Tracy et al. [20], it was observed that the CSA of the QFM peaks in the mid-thigh area (6–8-cm region), showing the greatest absolute amount of hypertrophy compared with proximal and distal regions. This is consistent to our results as the least correlation was seen at the CSA-15 level, with increasing correlation coefficients for CSA-20 and CSA-25. Whereas the lower correlation coefficient at CSA-15 is likely related to the anatomy of the muscle, where at this level only a small portion of the rectus femoris component is assessable for the CSA measurement (Fig. 1B), the mid-thigh region is best suitable to evaluate quadriceps volume changes using the CSA.

From a practical point of view, however, our findings demand a separate, dedicated MR examination of the thigh muscles in order to evaluate QFM insufficiency, as an extended proximal field-of-view of a routine post-operative knee MR exam would not cover the mid-thigh area.

Although overall, the correlation between the CSA at the three levels and the quadriceps TMV was high, we found a remarkable standard error of the estimate (SEE$_{TMV}$) of 15.2 %, 11.6 % and 8.1 % of the total quadriceps volume for CSA-15, CSA-20 and CSA-25, respectively. Similar values were obtained from the analysis of the operated and the non-operated legs subgroups. This means that for any given value of CSA, the mean bias of the predicted volume would be±1 SEE in approximately 68 % of cases and±2 SEE in 95 % of cases. Our results are in agreement with Tracy et al. [20], who reported a SEE of 7 % when the largest single CSA was used to predict the quadriceps volume, and with Morse et al. [19] who found mean SEEs of predicted compared to measured quadriceps volume of 26.8 %, 12.5 %, and 9.9 % (at 40 %, 50 %, and 60 % of the femur length, respectively). Compared to other volume estimation methods, e.g., based on the interpolation and deformation of a parametric specific object (mean SEE, 1.1 %) [15], CSA measurements perform inferiorly, but these methods are much more complex and time-consuming than a single CSA evaluation. Nevertheless, full muscle volumetry remains the gold standard for QFM size assessment in special in situations where the expected change in muscle size is relatively small. This could be the case for short-term follow-up examinations during rehabilitation programs or exams prior and after surgery.

CSA measurements of the QFM may be helpful to estimate the muscle strength, as QFM atrophy is correlated to the QFM strength [2–7]. The size of the quadriceps femoris muscle correlates with the muscle strength [5, 8, 39], but muscle

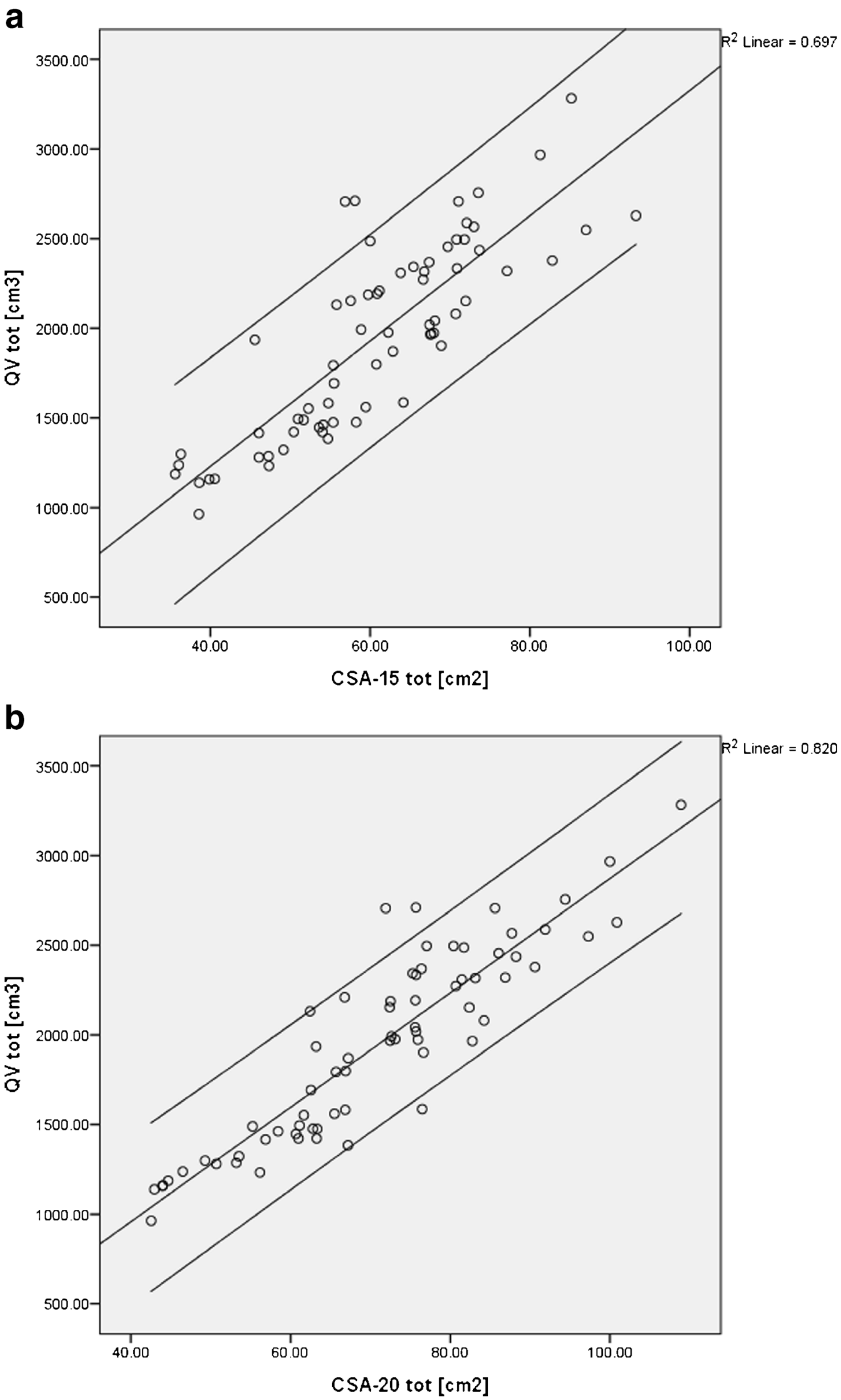

Fig. 2 Scatterplots and regression lines show the presence of a strong linear relationship between the quadriceps TMV and the measurements at the three levels: (*A*) CSA-15 (Pearson r=0.835, p<0.01), (*B*) CSA-20 (Pearson r=0.906, p<0.01) and (*C*) CSA-25 (Pearson r=0.956, p<0.01). *Solid central line* = regression line. *Solid upper and lower lines* = 95 % confidence intervals (±2 SEE)

weakness might also be due to increasing fat content (due to loss of muscular function [40] or muscle de-innervation [41]), which is not considered in CSA measurements. Therefore, other methods than trivial measurements of thigh circumferences have to be applied for the assessment of fatty muscle degeneration. These methods include the qualitative Goutallier classification on T1 sequences [42] and the quantitative fat-signal-fraction measurements on in- phase-based and opposed-phase-based chemical shift imaging, on MR spectroscopy and DIXON techniques [32, 40, 43–49], 3D ultrasound muscle volumetry [50] as well as for histopathologic examinations [43, 44, 51].

Our study has several limitations. One limitation was the relatively small number of cases, which was due to narrow inclusion criteria resulting in a well-selected, very homogenous study cohort. Second, due to practical reasons, we limited CSA measurements to only three levels and did not perform measurements at all levels. However, our methods were comparable to previous studies evaluating the CSA of the QFM [19, 20], allowing for direct comparison of our findings. Third, we outlined the outer margins of the quadriceps for both, volume and CSA evaluations, including the fascia and possibly a small amount of fat tissue interspersed between the fascia and the muscle and between the different muscle bellies. This could have introduced a systematic error, which should have similar biased the values for CSA and volume, and therefore would not have influenced the correlation analysis.

In conclusion, although a high linear correlation coefficient between quadriceps CSA of the mid QFM and TMV was found in our cohort of patients with ACL reconstructions, with the best correlation seen 25 cm above the knee joint line, the clinical application of CSA measurements to estimate the TMV is limited by a relatively large SEE. Thus, we recommend using CSA measurements only for gross estimation of muscles sizes or in those cases where large muscle volume differences are expected.

Acknowledgments The scientific guarantor of this publication is Erika Ulbrich. The authors of this manuscript declare no relationships with any companies, whose products or services may be related to the subject matter of the article. The authors state that this work has not received any funding. No complex statistical methods were necessary for this paper. Institutional Review Board approval was obtained. Written informed consent was obtained from all subjects (patients) in this study. Some study subjects or cohorts have been included in another substudy (not published yet) focusing on the vastus medialis muscle atrophy in patients after ACL reconstruction. Methodology: prospective, cross sectional study / experimental, performed at one institution.

References

1. Baugher WH, Warren RF, Marshall JL, Joseph A (1984) Quadriceps atrophy in the anterior cruciate insufficient knee. Am J Sports Med 12:192–195
2. Palmieri-Smith RM, Thomas AC, Wojtys EM (2008) Maximizing quadriceps strength after ACL reconstruction. Clin Sports Med 27: 405–424
3. Keays SL, Bullock-Saxton J, Keays AC, Newcombe P (2001) Muscle strength and function before and after anterior cruciate ligament reconstruction using semitendonosus and gracilis. Knee 8:229–234
4. Lindström M, Strandberg S, Wredmark T, Felländer-Tsai L, Henriksson M (2013) Functional and muscle morphometric effects of ACL reconstruction. A prospective CT study with 1 year follow-up. Scand J Med Sci Sports 23:431–442
5. Young A, Stokes M, Crowe M (1985) The size and strength of the quadriceps muscles of old and young men. Clin Physiol 5:145–154
6. Williams GN, Buchanan TS, Barrance PJ, Axe MJ, Snyder-Mackler L (2005) Quadriceps weakness, atrophy, and activation failure in predicted noncopers after anterior cruciate ligament injury. Am J Sports Med 33:402–407
7. Williams GN, Snyder-Mackler L, Barrance PJ, Buchanan TS (2005) Quadriceps femoris muscle morphology and function after ACL injury: a differential response in copers versus non-copers. J Biomech 38:685–693
8. Young A, Stokes M, Crowe M (1984) Size and strength of the quadriceps muscles of old and young women. Eur J Clin Investig 14:282–287
9. Järvelä T, Kannus P, Latvala K, Järvinen M (2002) Simple measurements in assessing muscle performance after an ACL reconstruction. Int J Sports Med 23:196–201
10. Callaghan MJ, Oldham JA (2004) Quadriceps atrophy: to what extent does it exist in patellofemoral pain syndrome? Br J Sports Med 38: 295–299
11. Sanada K, Kearns CF, Midorikawa T, Abe T (2006) Prediction and validation of total and regional skeletal muscle mass by ultrasound in Japanese adults. Eur J Appl Physiol 96:24–31
12. Miyatani M, Kanehisa H, Kuno S, Nishijima T, Fukunaga T (2002) Validity of ultrasonograph muscle thickness measurements for estimating muscle volume of knee extensors in humans. Eur J Appl Physiol 86:203–208
13. Engstrom CM, Loeb GE, Reid JG, Forrest WJ, Avruch L (1991) Morphometry of the human thigh muscles. A comparison between anatomical sections and computer tomographic and magnetic resonance images. J Anat 176:139–156
14. Narici MV, Landoni L, Minetti AE (1992) Assessment of human knee extensor muscles stress from in vivo physiological cross-sectional area and strength measurements. Eur J Appl Physiol Occup Physiol 65:438–444
15. Nordez A, Jolivet E, Südhoff I, Bonneau D, de Guise JA, Skalli W (2009) Comparison of methods to assess quadriceps muscle volume using magnetic resonance imaging. J Magn Reson Imaging 30:1116–1123
16. Walton JM, Roberts N, Whitehouse GH (1997) Measurement of the quadriceps femoris muscle using magnetic resonance and ultrasound imaging. Br J Sports Med 31:59–64
17. Jolivet E, Daguet E, Pomero V, Bonneau D, Laredo JD, Skalli W (2008) Volumic patient-specific reconstruction of muscular system based on a reduced dataset of medical images. Comput Methods Biomech Biomed Eng 11:281–290
18. Lund H, Christensen L, Savnik A, Boesen J, Danneskiold-Samsoe B, Bliddal H (2002) Volume estimation of extensor muscles of the lower leg based on MR imaging. Eur Radiol 12:2982–2987
19. Morse C, Degens H, Jones D (2007) The validity of estimating quadriceps volume from single MRI cross-sections in young men. Eur J Appl Physiol 100:267–274
20. Tracy BL, Ivey FM, Jeffrey Metter E, Fleg JL, Siegel EL, Hurley BF (2003) A more efficient magnetic resonance imaging-based strategy for measuring quadriceps muscle volume. Med Sci Sports Exerc 35: 425–433
21. Tracy BL, Ivey FM, Hurlbut D et al (1999) Muscle quality. II. Effects Of strength training in 65- to 75-yr-old men and women. J Appl Physiol 86:195–201

22. Harridge SD, Kryger A, Stensgaard A (1999) Knee extensor strength, activation, and size in very elderly people following strength training. Muscle Nerve 22:831–839
23. Sattler M, Dannhauer T, Hudelmaier M et al (2012) Side differences of thigh muscle cross-sectional areas and maximal isometric muscle force in bilateral knees with the same radiographic disease stage, but unilateral frequent pain – data from the osteoarthritis initiative. Osteoarthr Cartil 20:532–540
24. Strandberg S, Wretling ML, T W, A S (2010) Reliability of computed tomography measurements in assessment of thigh muscle cross-sectional area and attenuation. BMC Med Imaging 10:18
25. Barnouin Y, Butler-Browne G, Voit T, et al. (2014) Manual segmentation of individual muscles of the quadriceps femoris using MRI: a reappraisal. J Magn Reson Imaging 40(1):239–47
26. Esformes JI, Narici MV, Maganaris CN (2002) Measurement of human muscle volume using ultrasonography. Eur J Appl Physiol 87:90–92
27. Strandberg S, Lindstrom M, Wretling ML, Aspelin P, Shalabi A (2013) Muscle morphometric effect of anterior cruciate ligament injury measured by computed tomography: aspects on using non-injured leg as control. BMC Musculoskelet Disord 14:150
28. Marcon M, Ciritsis B, Laux C, Nanz D, Fischer MA, Andreisek G, Ulbrich EJ (2014) Quantitative and qualitative MR-imaging assessment of vastus medialis muscle volume loss in asymptomatic patients after anterior cruciate ligament reconstruction. JMRI. doi:10.1002/jmri.24777
29. Roos EM, Roos HP, Lohmander LS, Ekdahl C, Beynnon BD (1998) Knee Injury and Osteoarthritis Outcome Score (KOOS)–development of a self-administered outcome measure. J Orthop Sports Phys Ther 28:88–96
30. Barenius B, Forssblad M, Engstrom B, Eriksson K (2013) Functional recovery after anterior cruciate ligament reconstruction, a study of health-related quality of life based on the Swedish National Knee Ligament Register. Knee Surg Sports Traumatol Arthrosc 21:914–927
31. Shelbourne KD, Urch SE, Gray T, Freeman H (2012) Loss of normal knee motion after anterior cruciate ligament reconstruction is associated with radiographic arthritic changes after surgery. Am J Sports Med 40:108–113
32. Fischer MA, Nanz D, Shimakawa A et al (2013) Quantification of muscle fat in patients with low back pain: comparison of multi-echo MR imaging with single-voxel MR spectroscopy. Radiology 266:555–563
33. Shrout PFJ (1979) Intraclass correlations: uses in assessing rater reliability. Psychol Bull 86:420–428
34. Kundel HL, Polansky M (2003) Measurement of observer agreement. Radiology 228:303–308
35. Landis JKG (1977) The measurement of observer agreement for categorical data. Biometrics 33:159–174
36. Shaarani SR, O'Hare C, Quinn A, Moyna N, Moran R, O'Byrne JM (2013) Effect of prehabilitation on the outcome of anterior cruciate ligament reconstruction. Am J Sports Med 41:2117–2127
37. Akima H, Furukawa T (2005) Atrophy of thigh muscles after meniscal lesions and arthroscopic partial menisectomy. Knee Surg Sports Traumatol Arthrosc 13:632–637
38. Mizner RL, Petterson SC, Stevens JE, Vandenborne K, Snyder-Mackler L (2005) Early quadriceps strength loss after total knee arthroplasty. The contributions of muscle atrophy and failure of voluntary muscle activation. J Bone Joint Surg (Am Vol) 87:1047–1053
39. Nomura Y, Kuramochi R, Fukubayashi T (2014) Evaluation of hamstring muscle strength and morphology after anterior cruciate ligament reconstruction. Scand J Med Sci Sports. doi:10.1111/sms.12205
40. Fischer MA, Pfirrmann CW, Espinosa N, Raptis DA, Buck FM (2014) Dixon-based MRI for assessment of muscle-fat content in phantoms, healthy volunteers and patients with achillodynia: comparison to visual assessment of calf muscle quality. Eur Radiol 24(6):1366–75
41. Beeler S, Ek ET, Gerber C (2013) A comparative analysis of fatty infiltration and muscle atrophy in patients with chronic rotator cuff tears and suprascapular neuropathy. J Should Elb Surg Am Should Elb Surg 22:1537–1546
42. Goutallier D, Postel J-M, Bernageau J, Lavau L, Voisin M-C (1994) Fatty muscle degeneration in cuff ruptures: pre- and postoperative evaluation by CT scan. Clin Orthop Relat Res 304:78–83
43. d'Assignies G, Ruel M, Khiat A et al (2009) Noninvasive quantitation of human liver steatosis using magnetic resonance and bioassay methods. Eur Radiol 19:2033–2040
44. Fischer MA, Nanz D, Reiner C et al (2010) Diagnostic performance and accuracy of 3-D spoiled gradient-dual-echo MRI with water- and fat-signal separation in liver-fat quantification: comparison to liver biopsy. Invest Radiol 45:465–470
45. Borrello JA, Chenevert TL, Meyer CR, Aisen AM, Glazer GM (1987) Chemical shift-based true water and fat images: regional phase correction of modified spin-echo MR images. Radiology 164:531–537
46. Ma J (2008) Dixon techniques for water and fat imaging. J Magn Reson Imaging 28:543–558
47. Reeder SB, McKenzie CA, Pineda AR et al (2007) Water-fat separation with IDEAL gradient-echo imaging. J Magn Reson Imaging 25:644–652
48. Bruhn H, Frahm J, Gyngell ML, Merboldt KD, Hanicke W, Sauter R (1991) Localized proton NMR spectroscopy using stimulated echoes: applications to human skeletal muscle in vivo. Magn Reson Med 17:82–94
49. Dixon WT (1984) Simple proton spectroscopic imaging. Radiology 153:189–194
50. MacGillivray TJ, Ross E, Simpson HA, Greig CA (2009) 3D freehand ultrasound for in vivo determination of human skeletal muscle volume. Ultrasound Med Biol 35:928–935
51. Cassidy FH, Yokoo T, Aganovic L et al (2009) Fatty liver disease: MR imaging techniques for the detection and quantification of liver steatosis1. Radiographics 29:231–260