The Rectus Femoris Tendon Provides Sufficient Anatomical Length for a Quadrupled Graft in All Knees: An MRI Morphometric Analysis with Cadaveric Validation

Jana Nelson [1], **Alvin Karaqi** [2], **Philipp Braken** [3], **Richard Glaab** [4]*

(*) Corresponding Author: richard.glaab@hin.ch
1. University Children's Hospital Basel (UKBB), Pediatric Orthopedics, Spitalstrasse 33, 4031 Basel, Switzerland
2. Schulthess Clinic, Orthopedic Department, Lengghalde 2, 8008 Zurich, Switzerland
3. Cantonal Hospital Aarau, Department of Orthopedics and Traumatology, Tellstrasse 25, 5001 Aarau, Switzerland
4. Crossklinik, Bundesstrasse 1, 4009 Basel, Switzerland

Background: The isolated rectus femoris tendon (RFT) is an emerging autograft for knee ligament reconstruction due to the limitations of established autografts. Only the superficial layer of the quadriceps tendon is harvested, preserving the deep extensor mechanism.

Purpose: To characterize the dimensions of the RFT using MRI and cadaveric dissection and to derive a geometric model for graft configuration planning.

Methods: MRI morphometry was performed on 34 thighs (age 16-40 years), measuring total RFT length, width and thickness at the narrowest and widest points. Cadaveric dissection of 8 fresh-frozen thighs included in-situ measurements and harvest simulation using a standard tendon stripper. A geometric model, based on MRI-measured tendon thickness, was compared with published intraoperative and cadaveric measurements to predict achievable graft dimensions from the measured strip parameters.

Results: Mean total RFT length was 39 ± 7 cm on MRI and 33.5 ± 2.9 cm in cadavers (p = 0.002). After harvest, graft length was 30.8 ± 1.9 cm (harvest loss 8.1%), yielding a quadrupled graft length of 7.7 cm. The narrowest point was located approximately 5 cm proximal to the patella (width 18 ± 6 mm). Since only a portion of the tendon width is harvested, a strip of 9 mm width yields according to a geometric model a 4-fold graft diameter of approximately 8 mm; a 3-fold configuration with a 12 mm strip leaves approximately 98 mm of remaining graft for combined reconstructions.

Conclusion: The RFT consistently provides sufficient dimensions for a quadrupled autograft. These data provide the anatomical basis for preoperative planning: they identify the harvest corridor, quantify the strip width required for an expected quadrupled graft diameter of > 8mm, and localize the zone approximately 5cm proximal to the patella where the tendon is narrowest and thus most vulnerable during harvest.

What this study adds: This is the first study to combine in-vivo MRI morphometry with cadaveric validation of the isolated rectus femoris tendon. It shows that the tendon provides sufficient length for a quadrupled graft in all knees examined.

How this study might affect research, practice or policy: The data allow surgeons to plan strip width and fold configuration before surgery, including for combined ACL and anterolateral reconstructions. They also provide the anatomical basis for future biomechanical and clinical studies.

Study Design: Anatomical study

Level of Evidence: V

Keywords: Rectus femoris tendon; Quadriceps tendon; ACL autograft; Morphometry; Extensor mechanism

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Introduction

The quadriceps tendon (QT) has gained increasing popularity as a graft source for anterior cruciate ligament (ACL) reconstruction [1][2]. Outcomes are comparable to bone-patellar tendon-bone and hamstring autografts [3][4]. Due to the limitation of the established autografts like donor-site morbidity and anterior knee pain with bone-patellar tendon-bone grafts, hamstring weakness and the risk of undersized grafts with hamstring tendon harvest, and the limited number of available donor sites in revision and multi-ligament setting,

there is a motivation to find an alternative autograft. This trend has been accompanied by a shift in harvesting philosophy: from the full-thickness, bone-block technique originally described by Stäubli et al. [5] toward layer-specific, soft-tissue approaches that harvest only the superficial component of the extensor mechanism, preserving the substantial deep layers [6].

A key advantage of the QT as a graft source is that its size is less dependent on patient body habitus than that of hamstring autografts [7]. For hamstring tendon autografts, graft diameter correlates with height, weight, and sex, placing smaller patients at risk of grafts below the 8 mm threshold [8] [9]. Since the surgeon controls the harvest width of the QT, graft diameter becomes a surgical decision rather than an anatomical constraint.

Further reasons that the RFT is a plausible candidate: it is easily accessible, and it can be harvested without violating the extensor mechanism at the level of the patella [10].

Despite growing clinical adoption [11][12][13], systematic morphometric data remain limited. To our knowledge, no study has combined in-vivo imaging with cadaveric validation and no in-vivo morphometric data on this structure exist. All published dimensions to this date derive from cadaveric dissection or intra-operative measurements.

The purpose of this study was to characterize the dimensions of the RFT using MRI and cadaveric dissection with harvest simulation, to assess concordance between the two methods, and to derive practical implications for graft configuration planning.

Methods

Study Design and Ethics

This was an anatomical study comprising a retrospective MRI morphometric analysis and a cadaveric dissection with harvest simulation. The study was approved by the responsible ethics committee (BASEC ID 2024-01334) and conducted in accordance with the Declaration of Helsinki.

MRI Morphometry

MRI examinations were retrospectively identified from the institutional radiology database. The cohort predominantly comprised patients referred to imaging of proximal hamstring pathology, in whom the anterior thigh structures were incidental to the clinical indication. Inclusion criteria were age 16–40 years, complete T2-weighted sequences (axial, coronal, sagittal), and absence of quadriceps pathology, prior surgery, or significant artifacts. A total of 34 thighs met the inclusion criteria.

Imaging was performed on a 3-T system (Siemens Healthineers, Erlangen, Germany) using the institution's routine clinical thigh protocol, comprising T2-weighted turbo spin-echo sequences in axial, coronal and sagittal orientation. All measurements were obtained by a single experienced reader using the calibrated distance measurement tool of Sectra IDS7 (Sectra AB, Linköping, Sweden; reporting precision 0.1 mm). The effective measurement accuracy is bounded by the in-plane spatial resolution of standard clinical 3-T protocols (< 1 mm). Length and width were measured in-plane on sagittal and axial images, respectively, and are therefore robust at the reported precision; tendon thickness (mean 1.4 mm) approaches the spatial resolution limit and carries the greatest relative measurement uncertainty, which is why the graft diameter model was designed conservatively.

The following parameters were measured (**Figure 1 A-C**): total length of the RFT (sagittal plane, from proximal origin to patellar insertion); width and thickness at the narrowest point (axial plane) and its distance from the patellar insertion; width and thickness at the widest point (axial plane) and its distance from the patellar insertion.

Sample Size considerations

As a descriptive morphometric study, no hypothesis-testing power calculation was applicable; the sample size is instead justified by the precision of the descriptive estimates. With n = 34, population means are estimated with a 95 % confidence interval half-width of $1.96 \cdot SD/\sqrt{n}$, corresponding to ± 2.4 cm for total tendon length and ± 2.0 mm for width at the narrowest point. For the anatomical length criterion, the proportion of tendons with an MRI-detectable length of at least 28 cm - the length required for a quadrupled graft construct of 7 cm [14] - is reported with a Wilson score 95 % confidence interval, which remains valid at proportions close to 1.

Cadaveric Dissection and Harvest Simulation

Eight fresh-frozen thighs from four cadavers without prior surgery of the thigh or knee region were used. The specimens were thawed at room temperature for 24 hours before dissection. The RF muscle was carefully separated from the vastus intermedius along the natural fatty cleavage plane [14] [15]. After complete exposure, the RFT was measured in situ (total length, width at 30 cm proximal to the superior patellar pole).

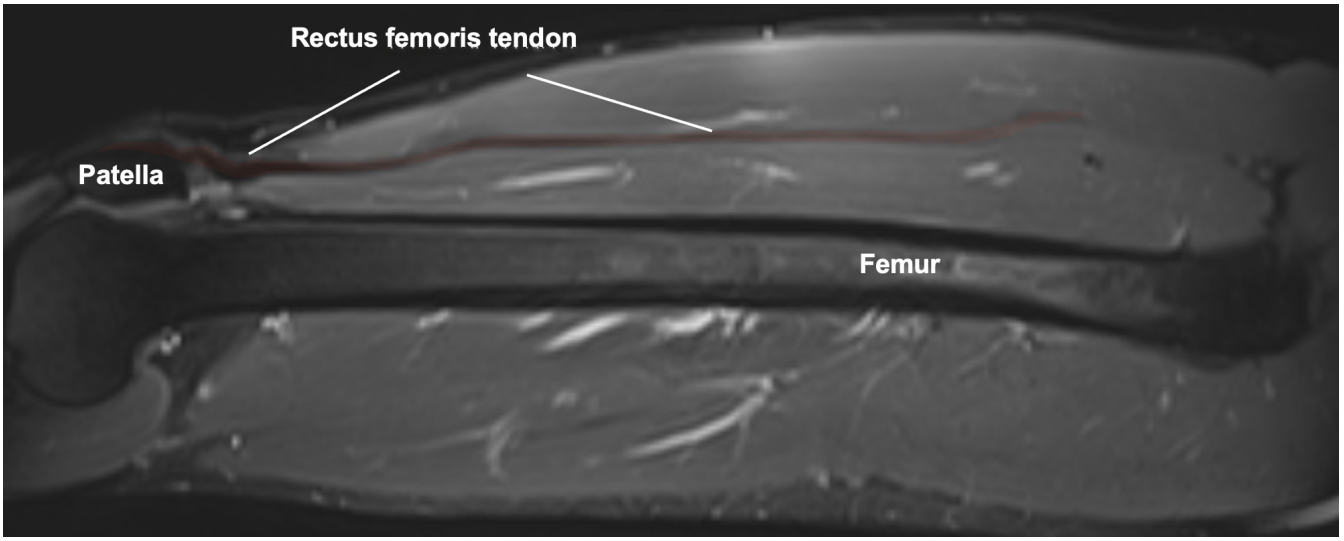


Figure 1A. MRI of the Rectus Femoris Tendon. Sagittal T2-weighted view - entire thigh.

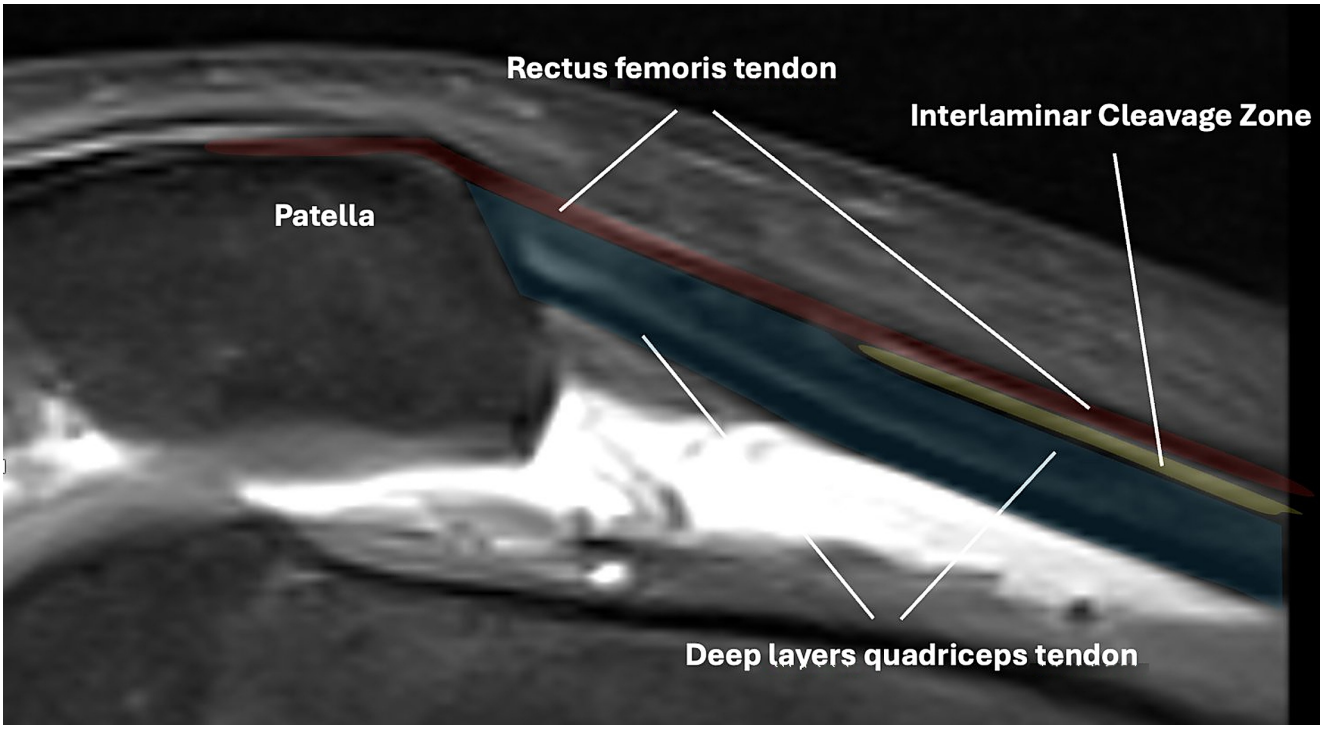


Figure 1B. MRI of the Rectus Femoris Tendon. Sagittal distal suprapatellar region - cleavage zone visible. red = RFT, yellow = interlaminar cleavage zone, blue = deep QT layers.

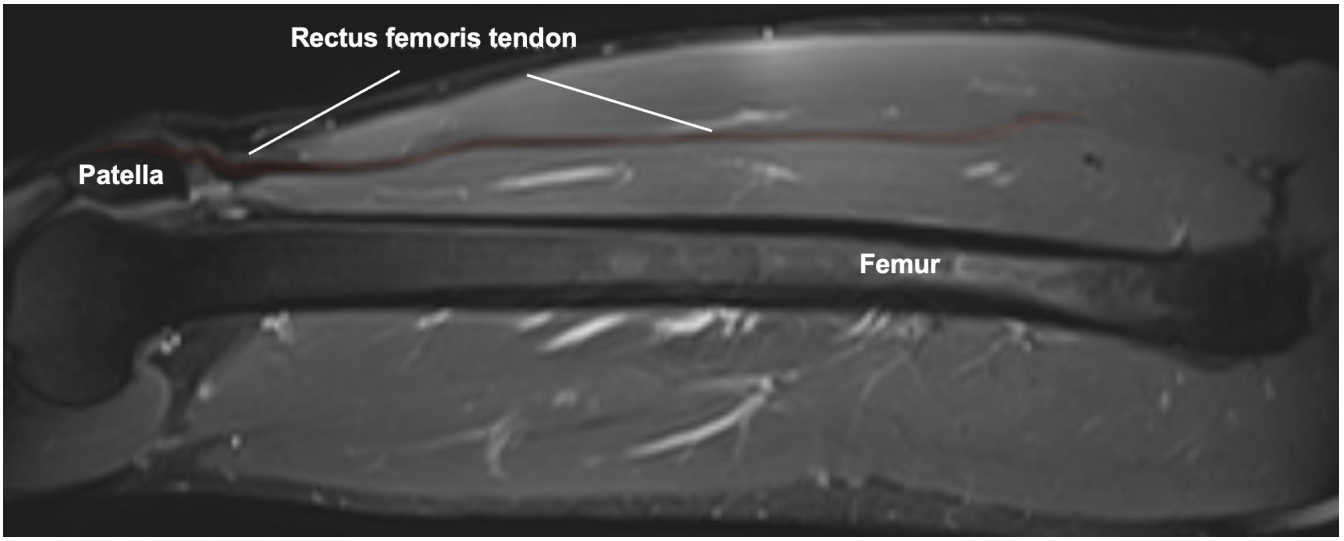


Figure 1C. MRI of the Rectus Femoris Tendon. Axial view - RFT (red), cleavage zone (yellow), deep layers (blue).

Subsequently, the tendon was harvested bidirectionally using a standard 7 mm open tendon stripper starting in the interlaminar cleavage zone. Only the superficial layer was harvested; the deep QT substance was left intact. The graft was measured for total harvest length and widest width. The quadrupled graft length was calculated by dividing the harvest length by four.

Graft Diameter Model

The achievable graft diameter was estimated using a geometric model. A flat tendon strip of width W and effective thickness T_eff, folded into N strands, yields a circular cross-section with diameter:

$d = 2 \times \sqrt{(N \times W \times T\_eff / \pi)}$

T_eff represents the effective tissue thickness of the prepared graft. In our MRI cohort, the mean RFT thickness was 1.4 ± 0.4 mm, and T_eff was set to this value for the primary model. Using T_eff = 1.4 mm provides a conservative, imaging-based prediction of achievable graft diameter.

Statistical Analysis

Descriptive statistics are presented as mean ± standard deviation and range. The comparison of RFT length between MRI and cadaveric in-situ measurements was performed using the Welch t-test. A p-value < 0.05 was considered statistically significant. Statistical analysis was performed using Python (SciPy v1.11).

Results

MRI Morphometry

The MRI cohort comprised 34 thigh examinations from patients aged 16-40 years. All 34 tendons (100%) met the predefined criteria (95% CI, 89.8-100.0%; Wilson score interval). The mean total RFT length was 39 ± 7 cm (range 32-47 cm) (**Figure 1A**). The narrowest point was located at a mean of 5.1 ± 3.0 cm proximal to the patellar insertion, with a width of 18 ± 6 mm and a thickness of 1.4 ± 0.4 mm (**Figure 1C**). The widest point was located at approximately 20.5 cm proximal, with a width of 51 ± 20 mm and a comparable thickness of 1.4 ± 0.4 mm.

Cadaveric Dimensions and Harvest Simulation

The cadaveric study included eight fresh-frozen thighs from four cadavers (**Table 1**). The mean total in-situ RFT length was 33.5 ± 2.9 cm (range 30-38 cm). The width at 30 cm proximal to the patella was 21 ± 7 mm. After harvest, the mean graft length was 30.8 ± 1.9 cm (range 28-34 cm), corresponding to a harvest loss of 2.7 cm (8.1%). The widest graft width was 28 ± 7 mm. The calculated mean quadrupled graft length was 7.7 cm. The deep QT layers remained intact after selective RFT harvest in all specimens (**Figure 2, 3A-B, 4**).

Table 1. Cadaveric morphometric data (n = 8).

Cadaver	Length of RFT (cm)	Width at 30cm (cm)	Stripped RFT length (cm)	Widest stripped width (cm)
1 left	33.8	1.8	31	3.8
1 right	32	1.7	32	4
2 left	36	3	30	2
2 right	36	2.3	34	2
3 left	38	1	30	2.7
3 right	30	1.5	30	2.4
4 left	31	3	31	2.6
4 right	31	2.5	28	3.2
Mean	**33.5**	**2.1**	**30.8**	**2.8**

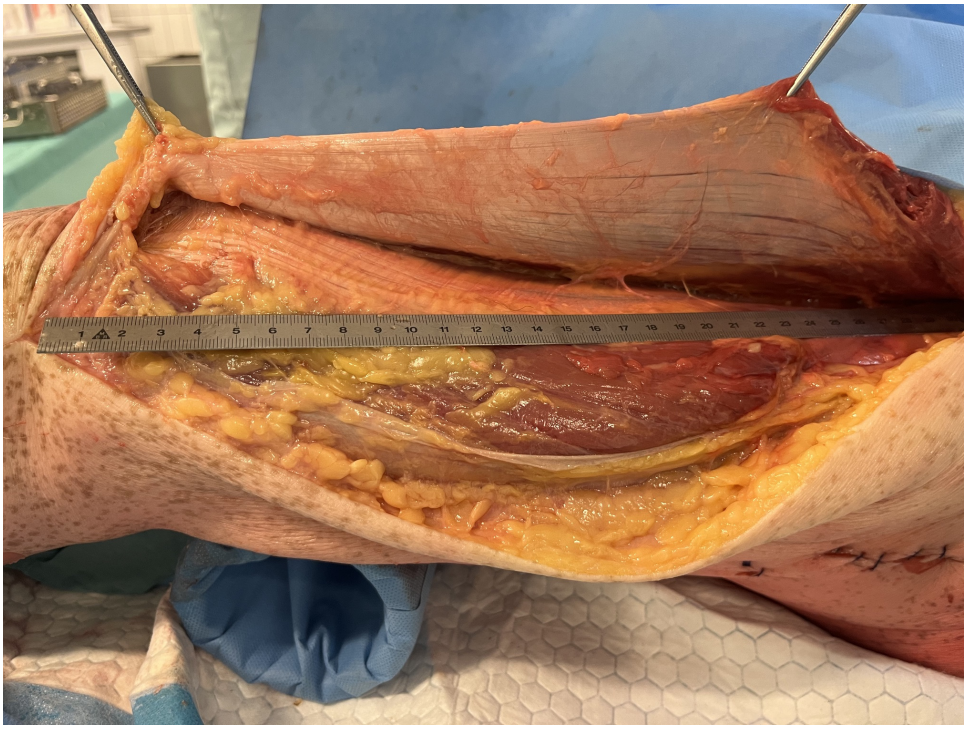


Figure 2. Cadaveric dissection of the rectus femoris tendon with in-situ measurement. The fatty cleavage plane separates the rectus femoris from the vastus intermedius.

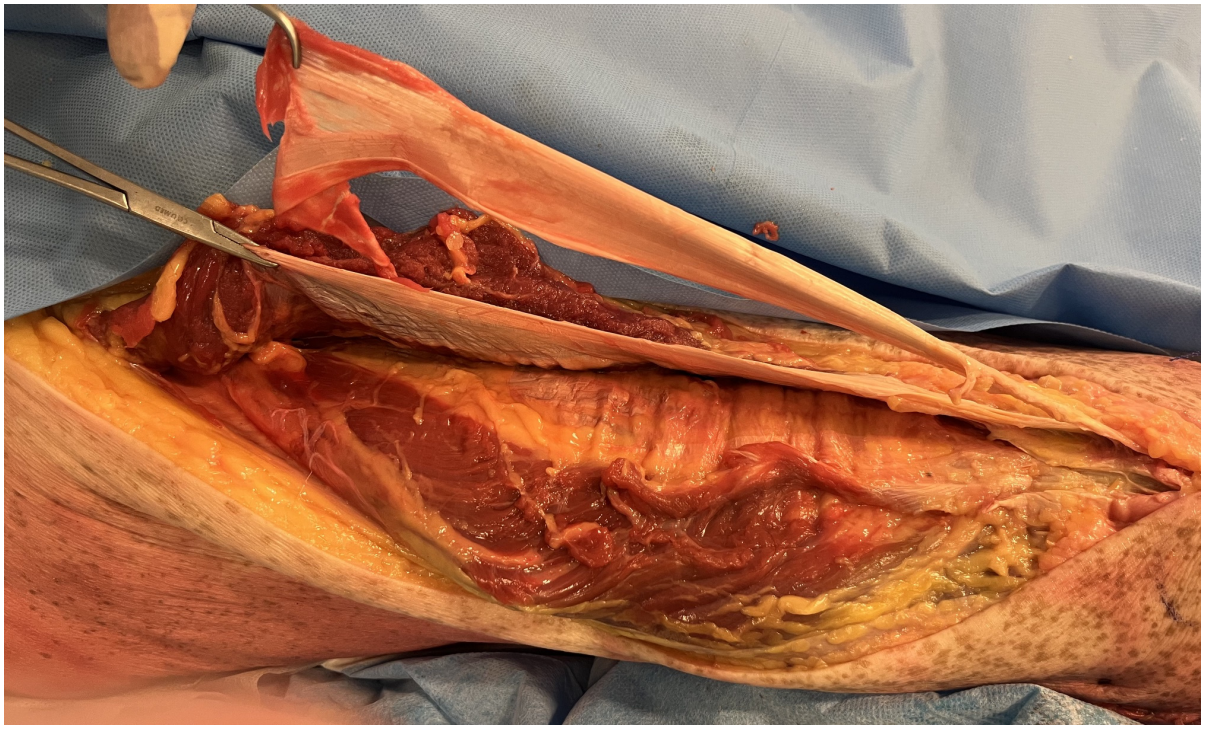


Figure 3A. Proximal harvested partial rectus femoris tendon.

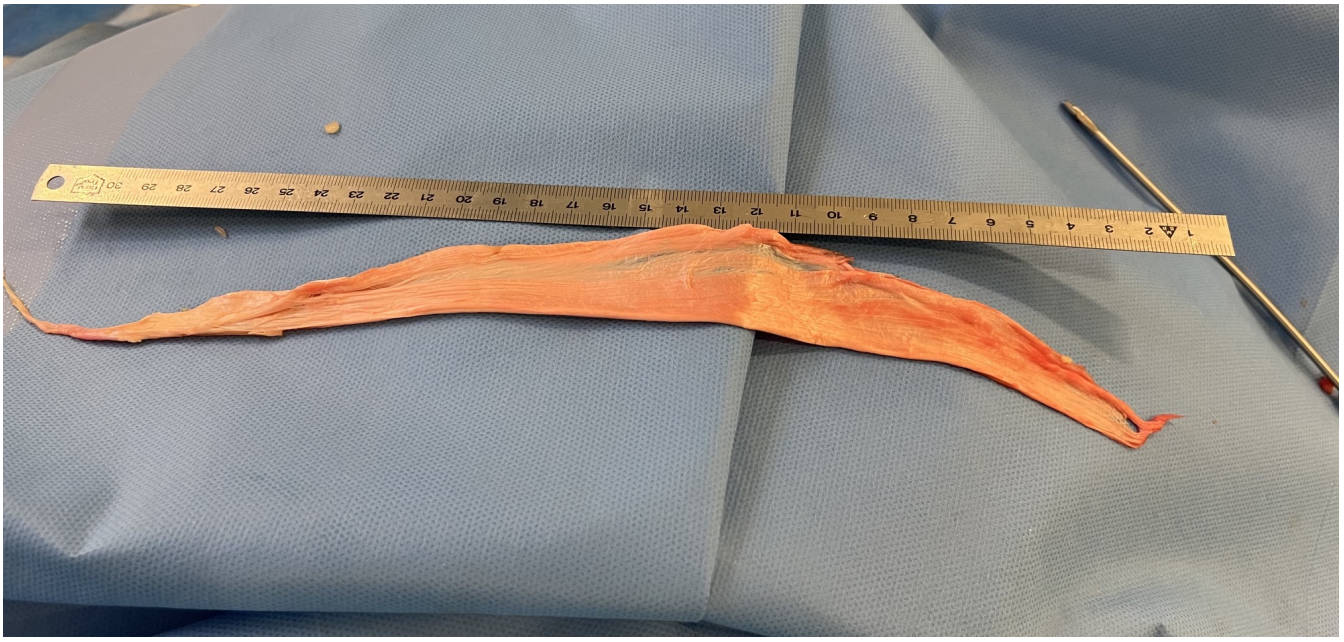


Figure 3B. Harvested graft with length measurement.

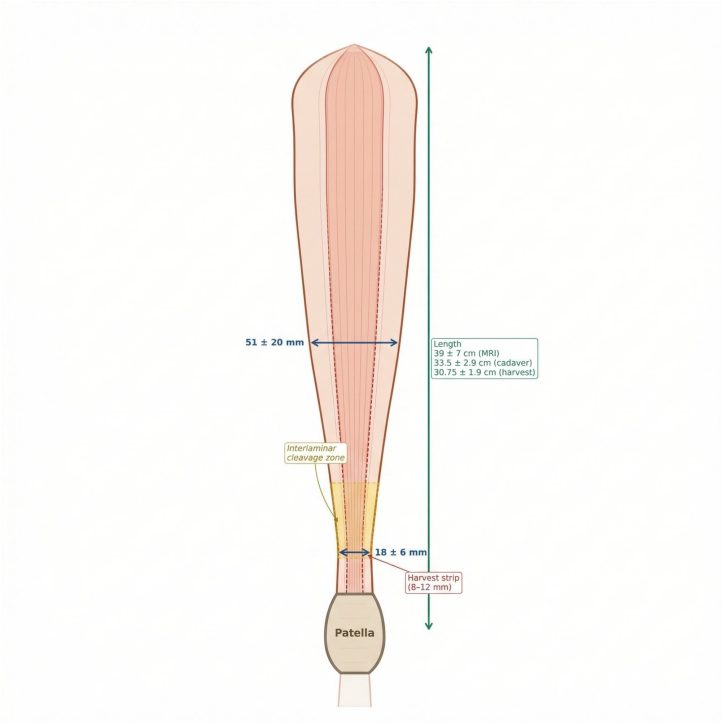


Figure 4. Schematic representation of the rectus femoris tendon dimensions. The RFT fans out from its narrow distal portion near the patella into a broad proximal fascial sheet. The narrowest point (18 ± 6 mm) determines the maximum harvest width; the harvest strip (red, 8–12 mm) follows the fiber direction and widens proportionally. The interlaminar cleavage zone (yellow) is located approximately 3–8 cm proximal to the superior patellar pole. Substantial residual tendon tissue is preserved on both sides of the harvest

MRI vs. Cadaveric Comparison

The mean total RFT length was significantly longer on MRI than in cadavers in situ (39 ± 7 cm vs. 33.5 ± 2.9 cm, p = 0.002), a difference of 5.5 cm (14.1%).

Qualitative Observations

In all cadaveric specimens, the RFT demonstrated a fan-shaped morphology with longitudinal fiber orientation (**Figure 4**), inserting broadly on the anterior patellar surface. A clear fatty cleavage plane separated it from the vastus intermedius in all cases (**Figure 2**). The entry point for the tendon stripper was consistently identified at 3-4 cm proximal to the superior patellar pole, where the RFT was free of fusion with adjacent structures – the interlaminar cleavage zone.

Graft Diameter Estimation

Using T_eff = 1.4 mm (MRI-based), the model predicts the graft diameters presented in **Table 2** and **Figure 5**. For a 4-fold configuration to achieve ≥8 mm diameter, a strip width of at least 9 mm is recommended; for a 3-fold configuration, at least 12 mm. Published data points from intraoperative and cadaveric studies consistently exceed these predictions (**Figure 5**), confirming that the MRI-based model provides a conservative estimate.

Table 2. Model-based predicted graft diameter by strip width and fold configuration (T_eff = 1.4 mm, MRI-based).

Strip width	4-fold Ø	3-fold Ø	Clinical application
7 mm	7.1 mm	6.1 mm	4-fold ACL (small patient)
8 mm	7.6 mm	6.5 mm	4-fold ACL (below 8 mm threshold)
9 mm	**8.0 mm**	**6.9 mm**	**4-fold ACL ≥8 mm (recommended)**
10 mm	8.4 mm	7.3 mm	4-fold ACL / 3-fold combined
12 mm	**9.2 mm**	**8.0 mm**	**3-fold ≥8 mm combined (ACL + LET/ALL)**

d = 2√(N×W×T_eff/π), T_eff = 1.4 mm (MRI-based, conservative estimate). Bold = recommended minimum strip width to achieve ≥8 mm graft diameter.

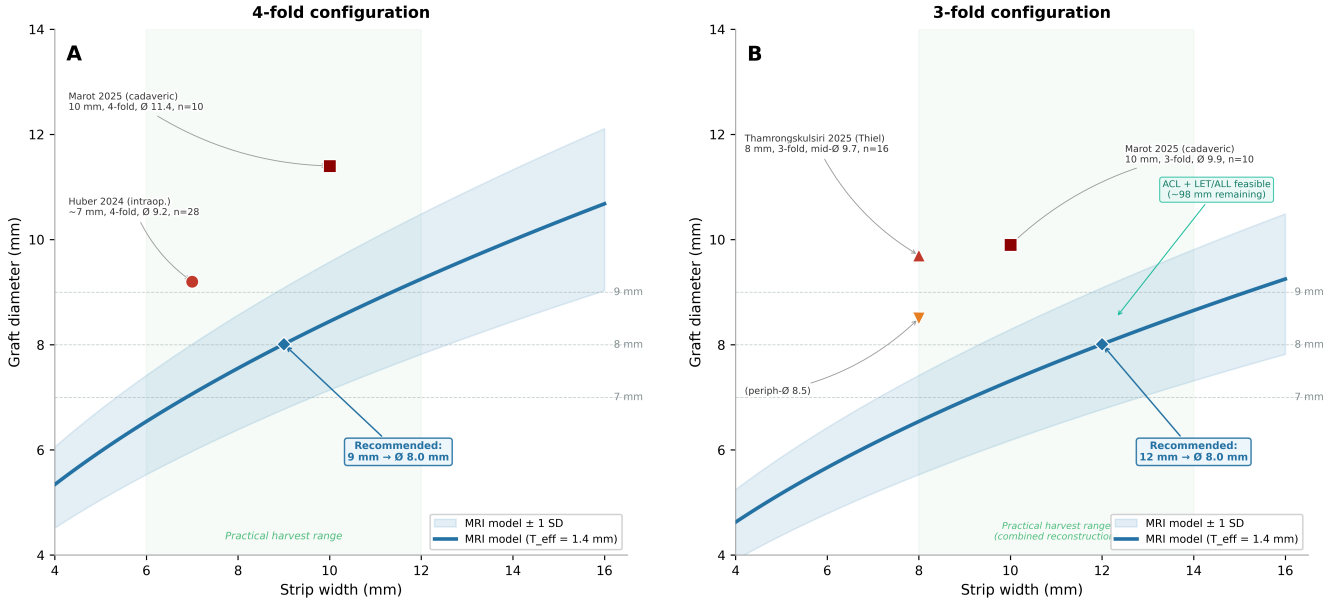


Figure 5. Prediction of how wide a strip should be chosen intraoperatively for 4-fold (A) and 3-fold (B) graft configurations. Solid line: MRI-based model (T_eff = 1.4 mm); shaded band: ± 1 SD of MRI thickness. Published data points from intraoperative [11] and cadaveric [14; 20] studies are superimposed; all exceed the MRI prediction due to tissue hydration, suture augmentation, and postmortem swelling effects. Diamond markers indicate recommended strip widths for ≥8 mm graft diameter. Dashed horizontal lines: 7, 8, and 9 mm thresholds.

Discussion

The most important finding of this study is that the RFT consistently provides sufficient length and width for a quadrupled autograft. Since only the superficial layer of the QT is harvested, the deep extensor mechanism - comprising the vastus intermedius, medialis, and lateralis tendons - remains intact, and substantial RFT tissue is left in situ on both sides of the harvested strip. To our knowledge, this is the first study to combine in-vivo MRI morphometry with cadaveric dissection and harvest simulation of the isolated RFT.

These data provide the anatomical basis for preoperative planning: they identify the harvest corridor, quantify the strip width required for an expected quadrupled graft diameter of >8mm, and localize the zone approximately 5 cm proximal to the patella where the tendon is narrowest and thus most vulnerable during harvest.

The Rectus Femoris as the Constant Superficial Layer

The selective harvest of the RFT depends on its reliable identification as the most superficial layer of the extensor mechanism. Stäubli et al. demonstrated on cryosections that the RF inserts broadly across the anterior surface of the patella, whereas the vasti converge predominantly at the superior patellar pole [5][15] (**Figure 1B**). This distinct

insertion pattern means that the RF layer can be identified and harvested from its patellar attachment distally without violating the deeper layers. Waligora et al. documented considerable variability in the deeper layers but the RF was consistently the most superficial component in all 20 specimens [16]. Strauss et al. confirmed this and identified a fuse point at a median of 48.7 mm from the patellar eminence line [17]. Marot et al. [14] identified two consistent tendinous confluence zones defining a reproducible harvest corridor in all specimens of 36.1 ± 13.0 mm. Grob et al. showed that the QT is formed by six elements including the tensor vastus intermedius, adding a fifth muscular component to the deeper architecture [18], and Olewnik et al. found accessory heads in over 60% of 128 limbs [19] - yet the RF remained identifiable as the superficial layer throughout. Our data confirm this: in all eight cadaveric specimens, the RFT was separable along the fatty cleavage plane, and in all 34 MRI examinations, it was delineated as a distinct structure (**Figure 1A, C**).

Morphometric Comparison

Two cadaveric studies of the isolated RFT have been published since our study was designed (**Table 3**). Marot et al. reported a mean RFT length of 30.1 ± 3.0 cm in 10 fresh-frozen specimens [14] and identified distal and proximal confluence zones at 22.4 and 58.5 mm above the patella. Thamrongskulsiri et al. reported 28.9 ± 1.0 cm in 16 Thiel-embalmed cadavers (mean age 64.7 years) [20]. Iriuchishima et al. reported 27.3 cm in 16 cadavers (mean age 78.8 years) [21]. RFT length varies inversely with donor age, with in-vivo measurements (present study: 39 ± 7 cm) exceeding cadaveric values. This likely reflects aside from the younger age in the in-vivo measurements, also postmortem tissue changes as well as in vivo elastic properties. Our cadaveric harvest length (30.8 cm) corresponds to published intraoperative values (Huber 32.4 cm, Rêgo ~30 cm, Barroso 30.8 cm) [11][12][22], and the calculated quadrupled graft length of 7.7 cm is sufficient for anatomic single-bundle reconstruction [23].

With this study we describe the morphometry of the RFT which provides a description of the tendon architecture and geometric measurements. However, structural properties like ultimate failure load, stiffness, cross-sectional area-normalized strength remain unknown.

Table 3. Published rectus femoris tendon length measurements.

Study	RFT length (cm)	Preservation
Marot et al. (2025)	30.1 ± 3.0	Fresh-frozen
Thamrongskulsiri et al. (2025)	28.9 ± 1.0	Thiel-embalmed
Iriuchishima et al. (2012)	27.3	Formalin-fixed
Present study (cadaveric)	33.5 ± 2.9	Fresh-frozen
Present study (MRI)	39 ± 7	In vivo

Graft Configuration Planning

A key contribution of this study is the derivation of a geometric model based on MRI-measured tendon thickness (**Table 2, Figure 5**). The model uses T_eff = 1.4 mm, corresponding to the mean MRI-measured RFT thickness in our cohort, and thus provides a conservative, imaging-based prediction of achievable graft diameter. Published intraoperative and cadaveric data consistently yield larger diameters than predicted by this model (**Figure 5**) [11][20][22]. Using our model-based graft prediction a 10mm strip folded into four-strand construct corresponds to an equivalent diameter of approximately 8.4 mm. Marot et al. [14] obtained a quadruple-strand diameter of 11.4 ± 0.8 mm from a 1-cm-wide strip. This systematic discrepancy is explained by three factors: (1) tissue hydration during intraoperative graft preparation increases the cross-sectional area; (2) suture augmentation at the fold points adds material to the graft circumference; and (3) in cadaveric specimens, postmortem tissue swelling further increases the measured thickness. The MRI-based model therefore represents a lower-bound estimate; actual intraoperative graft diameters may therefore exceed the predicted values.

The narrowest point of the RFT (18 ± 6 mm on MRI) determines the maximum harvest width. This is consistent with cadaveric data: Iriuchishima et al. reported a minimum width of 15.3 ± 2.9 mm at 4.8 cm from the patella in formalin-fixed specimens, while Marot et al. measured 20.1 ± 3.8 mm (range 15.0–29.0 mm) at 5 cm in fresh-frozen cadavers [21] [14]. Since only a portion of the tendon is taken, the strip width is a surgical decision rather than an anatomical constraint (**Figure 4**). Leaving 4-5 mm of residual tendon on each side, practical strip widths of 7-12 mm are achievable

while preserving substantial residual tendon substance. Based on our conservative MRI model (T_eff = 1.4 mm), a strip width of at least 9 mm is recommended for an isolated 4-fold ACL reconstruction to achieve ≥8 mm diameter (**Table 2**). Notably, Huber et al. achieved a mean intraoperative diameter of 9.2 mm with a narrower strip of only 6–8 mm [11], confirming that the MRI-based prediction underestimates achievable diameters. For combined reconstructions, a 3-fold configuration with a 12 mm strip is recommended to achieve ≥8 mm diameter by the MRI model, leaving approximately 98 mm of remaining graft length (based on mean harvest length 308 mm minus 3 × 70 mm ACL component), sufficient for a lateral extra-articular tenodesis (60-80 mm) or anterolateral ligament reconstruction (50–70 mm). This is consistent with the combined reconstruction concepts described by Sonnery-Cottet et al. [13] and Rêgo et al. [12].

It should be noted that the 8 mm minimum graft diameter threshold, while widely referenced, is primarily derived from hamstring graft studies and may not be universally applicable [23]. Koga et al. demonstrated that intercondylar notch width varies considerably and is significantly smaller in women; a graft that is appropriately sized for the individual patient's notch geometry may be more relevant than adherence to an absolute diameter cutoff [24]. The RFT's tunable diameter allows graft size to be matched to the patient's anatomy rather than being constrained by fixed donor tendon dimension.

Independence from Patient Anthropometrics

For hamstring tendon autografts, graft diameter is largely determined by the patient's body habitus: height, weight, and sex show moderate correlation with graft size, and smaller patients are at risk of grafts below the 8 mm threshold [8][9]. The isolated RFT harvest fundamentally differs in this regard. As only a partial strip is taken from a tendon that is substantially wider than the harvest, the surgeon controls the strip width intraoperatively by choosing the appropriate stripper aperture. Dworsky-Fried et al. confirmed this principle for the full-thickness QT, showing no significant correlation between anthropometric data and QT graft diameter on MRI [7]. The graft diameter is therefore a function of the chosen strip width and fold number - not of the patient's anthropometrics. This represents a practical advantage particularly in smaller patients, in women, and in populations where hamstring graft diameter may be limiting.

Harvest Loss

The mean harvest loss of 8.1% between in-situ and post-stripper length has not been quantified previously. This modest loss occurs at the proximal transition where the RFT fans into the muscle belly and supports the reliability of the tendon stripper technique.

Limitations

MRI measurements were performed by a single investigator without formal reliability testing. The MRI data are based on summary statistics; individual patient data were not available for subgroup analysis. Cadaveric demographics were limited, and the sample size (n = 8) is modest.

Another limitation is that the MRI cohort and the cadaveric cohort differ substantially in mean age, which reflects the nature of body donation programs. Tendon dimensions may vary with age through changes in muscle mass and tendon composition, and the cadaveric measurements should not be regarded as a direct validation of the values obtained in the younger, in vivo cohort but as a confirmation of the measurement approach and of the anatomical relationships described. Age-sensitive parameters (width, thickness) were therefore characterized exclusively in the in vivo MRI cohort, whose age profile matches the clinical target population.

Width measurements were obtained at different landmarks in the MRI and cadaveric components. The graft diameter model is a geometric approximation calibrated to a limited number of intraoperative data points; prospective validation with systematic intraoperative diameter measurements is needed. The MRI cohort comprised patients referred for hamstring pathology; however, quadriceps pathology was excluded.

No biomechanical testing was performed in this study and this precludes any recommendation for clinical use at this stage. Further studies are therefore needed to determine load-to-failure of quadrupled strips compared against hamstring and quadriceps tendon controls [25].

Conclusion

The RFT - the most superficial and anatomically most constant layer of the QT - consistently provides sufficient dimensions for a quadrupled autograft. Since only a partial strip of the tendon is harvested, the deep extensor mechanism and substantial residual RFT tissue remain intact. The surgeon determines the strip width intraoperatively, making graft diameter controllable and less dependent on patient body habitus.

These data allow preoperative estimation of the achievable graft diameter from a defined strip width and identify the harvest corridor in which a quadrupled graft of at least 8 mm can be expected, providing the anatomical basis required before biomechanical properties and clinical evaluation of this graft can be studied.

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Conflict of interest

The authors declare that they have no conflicts of interest relevant to the content of this manuscript.

Authors' contributions

Jana Nelson: Study conception and design; cadaveric data acquisition and dissection; analysis and interpretation of data; drafting of the manuscript; final approval of the version to be published; agreement to be accountable for all aspects of the work. Alvin Karaqi: MRI data acquisition and morphometric measurements; analysis and interpretation of imaging data; critical revision of the manuscript for important intellectual content; final approval of the version to be published; agreement to be accountable for all aspects of the work. Philipp Braken: Critical revision of the manuscript for important intellectual content; proofreading; final approval of the version to be published; agreement to be accountable for all aspects of the work. Richard Glaab: Study conception and design; supervision of data acquisition; analysis and interpretation of data; drafting and critical revision of the manuscript for important intellectual content; final approval of the version to be published; guarantor of the study and agreement to be accountable for all aspects of the work.

Patient consent statement

All patients whose MRI data were analyzed had provided general informed consent for the use of their clinical data for research purposes, in accordance with institutional policy. For the cadaveric component, specimens were obtained from donors who had provided written informed consent for the scientific use of their bodies during their lifetime, approved by the responsible ethics committee (BASEC 2024-01334).

Ethics statement

The study was approved by the responsible ethics committee (Ethikkommission Nordwest- und Zentralschweiz, EKNZ; BASEC ID 2024-01334) and conducted in accordance with the Declaration of Helsinki.

Data availability statement

The cadaveric data are presented in full in Table 1. For the MRI cohort, only aggregated data are available; individual measurements are no longer available.

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All figures and illustrations in this manuscript are original and were produced by the authors.

Use of generative AI / large language models

The authors used a large language model (Claude, Anthropic) to assist with language editing and manuscript structuring. The authors reviewed and verified all content and take full responsibility for the integrity, accuracy, and scientific content of the manuscript.

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