DOI: https://doi.org/10.30795/jfootankle.2025.v19.1873

Original Article

Optimization of MRI measurements of calf muscle atrophy following acute Achilles tendon rupture

Ibrahim El Haddouchi[1], Anders Brøgger Overgård[1], Maria Swennergren Hansen[1], Per Hölmich[1], Kristoffer Weisskirchner Barfod[1]

1. Copenhagen University Hospital, Hvidovre, Denmark.

Abstract

Objective: Investigate whether single slice cross- sectional area (CSA) measurement could be used as a surrogate for volumetric measurement on magnetic resonance imaging (MRI) in evaluating calf muscle atrophy after Achilles tendon rupture (ATR). We hypothesized that atrophy estimated by single slice CSA measurement had an R-squared (R^2) value above 0.7 when compared to volumetric measurements.

Methods: This was a cross-sectional study of patients one year after ATR. An MRI of both calves was performed. Muscle volume was calculated by measuring CSA of the muscles of the triceps surae and the deep flexors on axial slices every 2 cm. The limb symmetry index (LSI) was used to estimate atrophy. The two methods for assessing atrophy, single slice CSA and volumetric measurement, were compared by fitting a linear regression model and calculating the R^2-value.

Results: The strongest correlation was obtained when measuring CSA of the triceps surae ($R^2 = 0.780$), soleus ($R^2 = 0.636$), medial gastrocnemius ($R^2 = 0.612$) and lateral gastrocnemius ($R^2 = 0.556$) 26 cm above talus, and the deep flexors ($R^2 = 0.493$) 14 cm above talus.

Conclusions: Cross- sectional area measurement on a single MRI slice can be applied as a surrogate for volumetric measurements when investigating atrophy of the triceps surae muscle group as a whole. However, this approach is not suitable when investigating the individual parts of the muscle.

Level of evidence III, Cross-sectional comparative study.

Keywords: Achilles tendon; Rupture; Magnetic Resonance Imaging; Muscular atrophy; Cross-sectional studies.

Introduction

Changes in calf muscle volume are common after acute Achilles tendon rupture (ATR)[1]. Muscular change following ATR is affected by a complex combination of tendon elongation, type of rehabilitation, and sedentary lifestyle[2]. Muscle atrophy has been reported as a common long-term problem in ATR causing changes in gait pattern and reduced total concentric plantar flexion power[3-5].

Quantifying muscle compartment size on magnetic resonance imaging (MRI) can be performed in two ways: volumetric or cross-sectional area (CSA) measurement. Volumetric measurement is time-consuming and requires more data collection than CSA measurement[6,7].

The current literature, on optimizing the process of muscle volume assessment, suggests that the volume of the individual muscles of the triceps surae can be estimated using two primary methods: 1) calculating the muscle length byand the largest measured CSA[8-10] or 2) converting the average of the largest CSA and the CSAs proximal and distal to the largest CSA to a volume using a fitted regression model[11]. The commonality between the two methods is the need for measurements on several slices and/or a view of the complete muscle.

Since not all MRIs provide a field of view of the full length of the soleus and gastrocnemius muscles, we aimed to simplify the method of volume expression further by applying the

Study performed at the Sports Orthopedic Research Center - Copenhagen (SORC-C), Hvidovre Hospital, Hvidovre, Denmark.

Correspondence: Ibrahim El Haddouchi. Kettegård Alle 30, 2650 Hvidovre, Denmark. **Email:** ibrahim.haddouchi@outlook.com. **Conflicts of interest:** None. **Source of funding:** None. **Date received:** January 27, 2024. **Date accepted:** March 16, 2025.

How to cite this article: El Haddouchi I, Overgård AB, Hansen MS, Hölmich P, Barfod KW. Optimization of MRI-measurements of calf muscle atrophy following acute achilles tendon rupture. J Foot Ankle. 2025;19(1):e1873.

measurement of one single slice to estimate the muscle volume of the individual muscles in the triceps surae.

The purpose of the study is to investigate the possible replacement of volumetric measurement by single slice CSA measurement when examining the volumetric changes to the calf muscles after acute ATR utilizing MRI. Using volumetric measurements on MRI as the gold standard, we hypothesized that atrophy estimated by single- slice CSA measurements of the individual muscles had an R-squared (R^2) value above 0.7 when compared to the golden standard method.

Methods

The study was performed as a cross-sectional study investigating patients one year after acute ATR. The study was reported following the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) checklist[12].

Study setup

An MRI was performed one year after ATR on the injured and the uninjured lower leg. Atrophy of the injured leg was expressed as the relative atrophy compared to the uninjured leg and was calculated using the limb symmetry index (LSI). Relative atrophy or LSI was defined as the scores of the injured leg divided by the scores of the uninjured leg presented as a percentage:

$$\text{Limb symetry index (LSI)} = \frac{\text{injured leg}}{\text{uninjured leg}} \cdot 100$$

The LSI values determined by volumetric measurement were then compared with those determined by single slice CSA measurement.

Study participants

Patients were recruited through an ongoing randomized controlled trial investigating functional and patient-reported outcomes after acute ATR[13,14]. The inclusion criteria were: age 18 to 65, examination in the outpatient clinic within four days after injury, total ATR, initial treatment with split plaster cast with the ankle in maximal plantar flexion started within 24 hours after injury, ability to attend rehabilitation and post examinations, and ability to speak and understand Danish. The exclusion criteria were previous ATR in either leg, examination in the outpatient clinic later than four days after injury, tendon rupture at either insertion, corticosteroid or fluroquinolone treatment within the last six months, diabetes medical treatment, prior injury resulting in reduced function of the legs, contraindication for surgery, American Society of Anaesthesiologists (ASA) score ≥ 3. All patients were given, oral and written, information concerning the project before informed consent was obtained.

MRI measurements

The MRI measurements were determined by measuring and studying the three muscles of the triceps surae (soleus, medial gastrocnemius, and lateral gastrocnemius), both individually and the muscle group as a whole, represented by the sum of the three muscles. The deep flexors (flexor hallucis longus, flexor digitorum longus, and tibialis posterior) were measured and studied as one unified group.

The scans were conducted on a 1.5T MRI system (Magnetom Avanto, Siemens, Erlangen, Germany). The MRI sequence protocol applied was a 2D gradient echo sequence (Siemens DESS (Dual Echo Steady State) package). This protocol enabled a reconstruction of the scan, constructing 1 mm axial slices with 1 mm interslice distance, thereby creating a 2 mm distance between each slice. Both calves were scanned from just inferior to the heel and as proximal as our field of view allowed. The scans were performed with patients in the supine position and with the ankle in neutral position (90 degrees) secured by custom-made braces.

The CSA was measured manually by marking the muscle compartments individually using the "closed polygon"" function in OsiriX Lite© version 12.0 (Figure 1). The most distal border of the measurement was defined by the most cranial aspect of the talus bone. The measurement started at the most proximal axial slide where the talus was visualized, being the distal reference slide. From there, CSA was measured on every 10th slice (20 mm intervals) cranially. When a muscle compartment originated within this interval, the part of the muscle distal to the first CSA measurement of the muscle compartment was not included in the volume. The measurements were performed by two investigators (ABO and IEH). ABO measured 18 subjects and IEH 36 subjects. Conformity of the measuring method was achieved through a thorough, written, step-by-step examination protocol. Subsequently, IEH and ABO performed one measurement of a scanning image together to adjust for possible differences.

The proximal origin of the gastrocnemius muscles at the femoral condyles was not visualized as no MRI coil allowed for a field of view of the necessary length in the Magnetom Avanto MRI scanner. Consequently, the proximal border of the CSA measurement was defined as the most proximal 20 mm interval section in which no blurring of the picture was present. By involving the same number of slices with 20 mm intervals on both lower legs, we ensured that the distance measured from the talus was the same on the injured and uninjured leg.

Calculation of muscle volume – the gold standard

The muscle volume between two CSAs was calculated as cones with irregular bottoms using the formula: Volume = $h/3 \times (A_1 + \sqrt{(A_1 \times A_2)} + A_2)$, where h is the height of one cone and equals 20 mm, while A_1 and A_2 are the bottom and top of the cone, respectively, being the CSA measurements of the individual muscle compartments. The muscle volume of the individual muscles was then determined by adding up the values of the cone volumes for the muscle in question. This calculation method was previously used by Heikkinen et al.[15]. Furthermore, Pons et al.[7] found that assessment of muscle volume by this method was the most valid and reliable method when studying the calf muscles.

Proposed CSA measurement methods

Five methods of single slice CSA measurement were investigated and evaluated. With 20 mm between every slice, the proposed practices were:

1. CSA measurement of all the calf muscles on the slice with the largest cumulative CSA of all muscle bellies.
2. The slice with the largest cumulative CSA was found by adding the measured CSA of the four muscle compartments and choosing the slice with the largest sum.
3. CSA measurement of the individual calf muscles on the slices with the largest individual area.
4. The slice with the largest measured CSA of the individual muscles was identified and chosen.
5. CSA measurement of the calf muscles on a slice with a defined distance from the most cranial aspect of the talus bone.
6. The 13th slice, being 26 cm proximal to the distal reference slice, was chosen for every muscle.
7. CSA measurement of the calf muscles on the slice corresponding to 30% of the leg length.

   The leg length of every patient was measured, and the slice corresponding to 30% of the leg length was found.
8. CSA measurement of the deep flexors on four predefined distances from the most cranial aspect of the talus.

   The 3rd, 5th, 7th and 9th slice (being 6 cm, 10 cm, 14 cm, and 18 cm from the distal reference slide) were chosen for measurement of the deep flexors only.

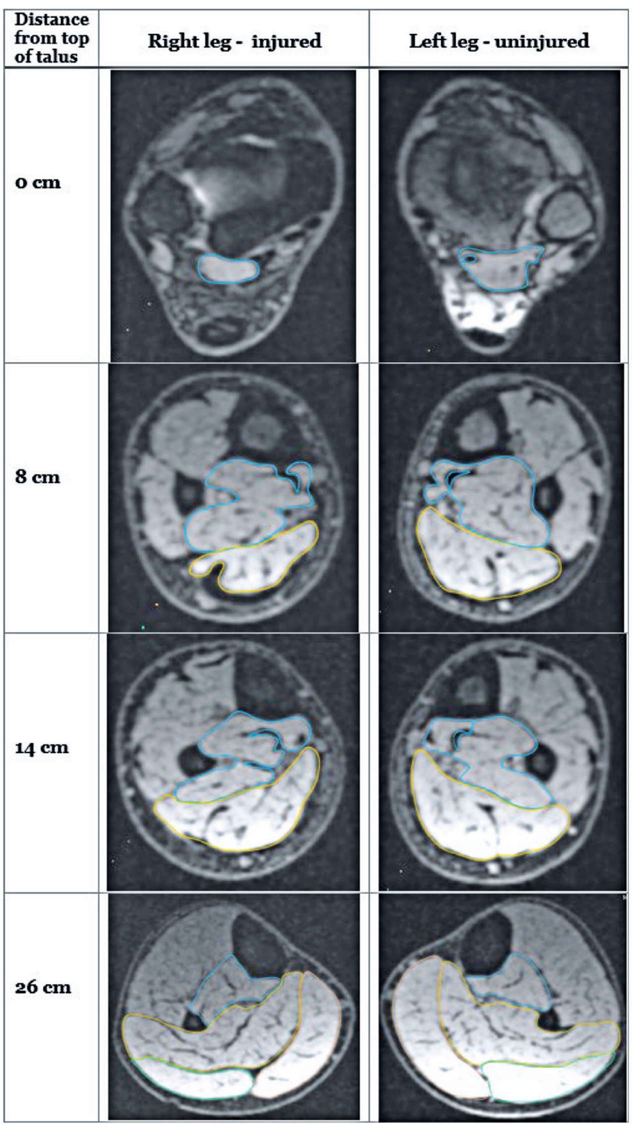

Figure 1. Axial slices from both legs of a random patient on four different distances from the top of the talus. The outlined regions define the muscle compartments of the deep flexor complex (blue), the soleus muscle (yellow), the medial head of the gastrocnemius muscle (orange), and the lateral head of gastrocnemius muscle (green).

Statistical analysis

With the volumetric measurements being the gold standard, LSI determined from the five methods of single slice CSA measurements were compared to LSI determined from the volumetric measurements. To evaluate the degree of variation between the volumetric measurement and the five models for single slice CSA measurement, a linear regression model was fitted for each model, and the R^2-values were determined as a measure of variance. After consultation with a statistician (TK) it was decided not to adjust for confounders, as each patient was its control and no relevant confounders were recognized.

Results

Sixty patients were enrolled, and 54 contributed to MRI data at one-year follow-up due to dropout (2 because ofwere pregnancypregnant, 1 because of long distance transport, and 3 with no reason). The distribution of the 54 participants was as follows: 45 males and 9 females, age (mean ± SD) 41.9 ± 9.2 years, height 178 ± 8 cm, and body mass index (BMI) 26.3 ± 3.6.

The results of the linear regression analyses are illustrated graphically in Figure 2, and the R^2-values are presented in Tables 1 and 2. The highest R^2-values for triceps surae (R^2 = 0.780), the soleus (R^2 = 0.612), and medial gastrocnemius (R^2 = 0.636) muscles were determined with method 3 (described in methods section). In terms of the lateral gastrocnemius, the strongest correlation (R^2 = 0.627) was obtained with method 2.

The deep flexors were examined further in method 5 where CSA was measured in shorter distances from the talus (Figure 3). The highest R^2-value (R^2 = 0.493) was obtained when measuring the CSA 14 cm above the talus.

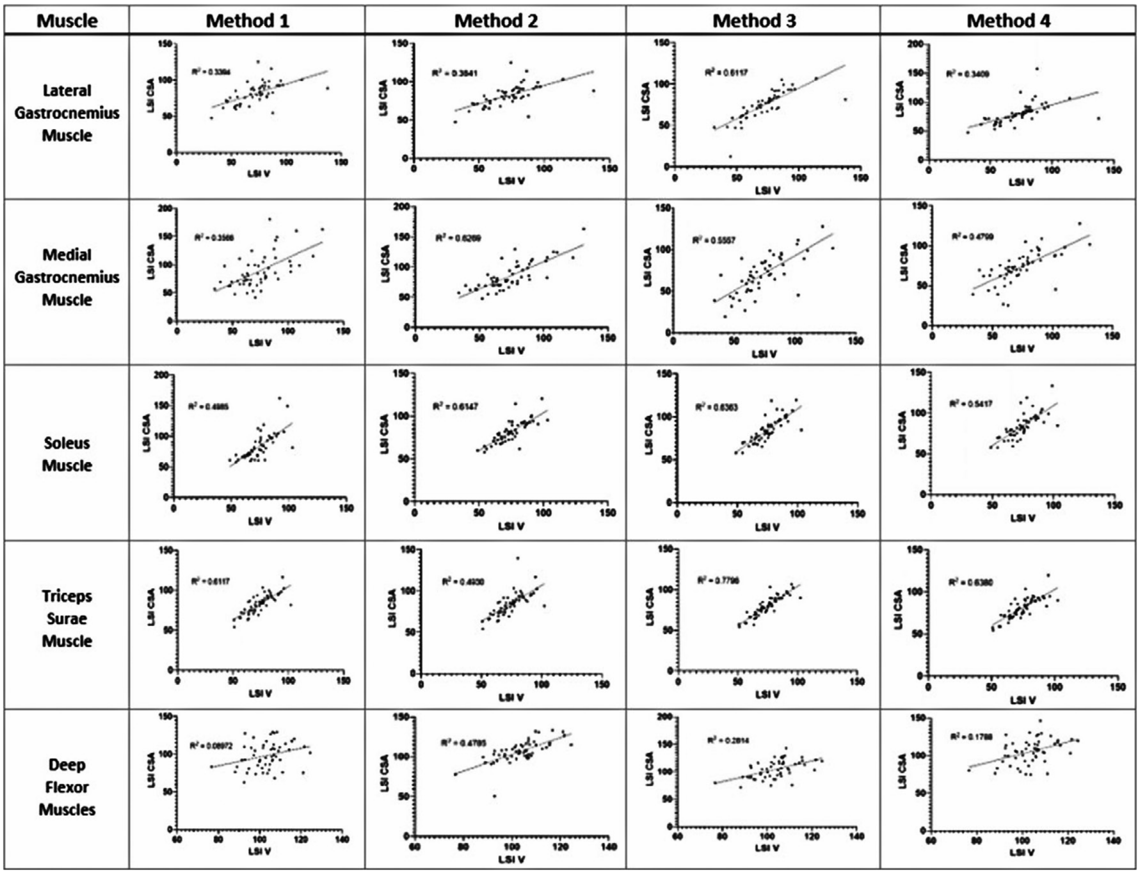

Figure 2. The graphs illustrate the correlations between the Limb Symmetry Index (LSI) derived from cross-sectional area (CSA) measurement on the y-axis and volumetric (V) measurement on the x-axis. Method 1: CSA measurement on the slice with the largest cumulative area of all muscle bellies. Method 2: CSA measurement on the slice with the largest area of the respective muscle. Method 3: CSA measurement 26 cm above the talus. Method 4: CSA measurement on the slice corresponding to 30% of the leg length.

Table 1. The R^2-values of the linear regression analyses for each muscle with the four methods.

R^2 - value	Method 1	Method 2	Method 3	Method 4
Medial gastrocnemius	0.339	0.384	0.612	0.341
Lateral gastrocnemius	0.357	0.627	0.556	0.480
Soleus	0.499	0.615	0.636	0.542
Triceps surae	0.612	0.493	0.780	0.638
Deep flexors	0.0897	0.479	0.281	0.179

Table 2. The R^2-value of the linear regression analyses for the deep flexors at four different distances from the talus.

R^2 - value	6 cm above talus	10 cm above talus	14 cm above talus	18 cm above talus
Deep flexors	0.214	0.437	0.493	0.323

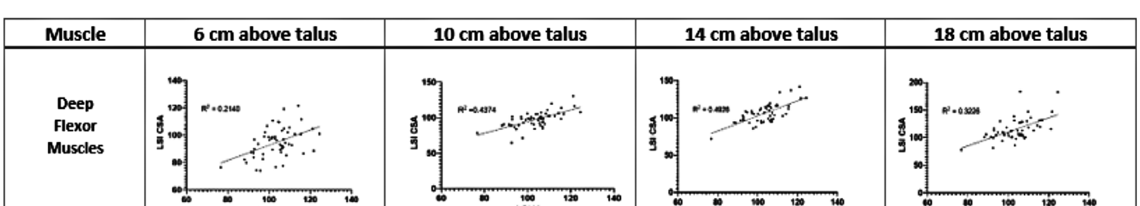

Figure 3. The graphs illustrate the correlations between the Limb Symmetry Index (LSI) derived from cross-sectional area measurement on the y-axis and LSI derived from volumetric measurement on the x-axis when investigating the deep flexors in 4 different distances from the talus.

Discussion

The most important finding of the study was that single slice CSA measurement, when examining the triceps surae as a muscle group, method 3 as described in section 2.5, correlated with volumetric measurement with an R^2-value above 0.7. However, single slice CSA measurement could not be used as a surrogate for volumetric measurement when investigating the individual muscle bellies as none of the proposed methods for single slice CSA measurements revealed R^2-values above 0.7.

When determining the CSA of the muscles 26 cm above the talus, method 3 yielded the strongest correlation amongst the four methods tested. Two factors may explain this finding. Firstly, the muscles investigated in all patients were consistently apparent to be 26 cm from the talus on the MRI. Secondly, the CSAs of the muscles are meticulously measured at the same distance from the talus on both the injured and the uninjured leg.

Assessing atrophy by CSA measurement of all the muscles on the slice with cumulative largest area, hence when applying method 1, yielded the weakest correlation. This method did not account for the variation in the individual muscles since not all triceps surae muscles were necessarily prominent on the slice with the cumulative largest area. Method 4, the CSA measurement of the muscles on the slice corresponding to 30% of the leg length, considers the difference in the individual patients' leg length. Therefore, it was surprising that the correlations in this method were inferior compared to method 3. We do not have a qualified physiological explanation for this finding. The distance of 30% was chosen as it showed the best correlations when compared with other distances.

Investigation of the deep flexors did not show a good correlation, but the best attainable correlations and R^2-values were achieved when the CSA measurement was performed within shorter distances from the talus. Contrary to the other muscles, the deep flexor complex is larger and more prominent on the CSAs with shorter distances to the talus, which might explain why the correlation was stronger closer to the ankle joint. This observation is supported by the finding that the highest R^2-value when investigating the correlation between CSA and volumetric measurement of the deep flexors was obtained when measuring the CSA 14 cm above talus ($R^2 = 0.493$) and is almost the same as the R^2-value obtained when measuring the CSA of the deep flexors on the slice where it had the largest area ($R^2 = 0.479$).

Quantification of muscle volume has been intensely studied over the past decades[(7)], but only four studies have investigated the muscle volume of the triceps surae evaluated by MRI[(8-11)]. A simple model assessing muscle volume from a product of the largest measured CSA and the length of the muscle has been validated in three studies. Albracht et al.[(8)] examined the method for individual muscle volumes within the triceps surae in thirteen healthy young athletes and found good validity (root mean squares 4%-7%) for all muscles in the triceps surae. Mersmann et al.[(9)] investigated 32 individuals (untrained individuals (n = 13), endurance (n = 9) and strength trained (n = 10) athletes). They found that the metrological quality was good when investigating the medial gastrocnemius (RMS 4.8%) and moderate when investigating the lateral gastrocnemius and soleus muscle (RMS 7.9%-8.3%)[(7,9)]. Finally, Vanmechelen et al.[(10)] investigated the measurement in healthy individuals and individuals with cerebral palsy and found a strong validity (R^2 between 0.955 and 0.988). The mentioned studies compared CSA and volumetric measurement on the same leg, with no prior injury or intervention.

One study investigated muscle change of the left lower limb in 20 subjects after 56 days of bed-rest by performing MRI at day 0 and day 56 and compared several methods of CSA measurement with slice-by-slice manual segmentation in detecting muscle change[(11)]. Five algorithms were tested; 1) the largest CSA, 2) the largest CSA and progressively incorporating the 13 slices immediately proximal and distal to it into an average and hereby evaluating the number of slices needed to attain the best correlation, 3) the same as algorithm two2 except that every second slice was taken distally and proximally, 4) the CSA at 30%, 50% and 80% of the muscle length, 5) the most proximal CSA of the muscle. To investigate the correlation a linear regression analysis was performed and it was found that algorithm 2 had the best correlations for lateral gastrocnemius ($R^2 = 0.97$, the average of the largest CSA and the CSA of the 7 slices proximal and distal to it), medial gastrocnemius ($R^2 = 0.99$, the average of the largest CSA and the CSA of the 2 slices proximal and distal to it) and soleus ($R^2 = 0.98$, the average of the largest CSA and the CSA of the 4 slices proximal and distal to it). Thus, a reduction of ~60% in the total number of manual CSA measurements was feasible in estimating changes in the muscle volume of the muscles in the triceps surae.

Our study is the first to investigate different methods of assessing muscle changes in the triceps surae after ATR. Considering the results from our study, applying CSA measurement on a single slice on MRI can be used as a surrogate for volumetric measurements when investigating atrophy of the triceps surae muscle as a whole, but we cannot recommend CSA measurement of the individual calf muscles based on a single MRI slice. If single slice CSA measurement based on LSI is to be utilized, the most precise estimations seem to be achieved by performing the CSA measurement of the muscles on slices where they are the most apparent and prominent.

Limitations

No test-retest was performed on the measurements; therefore, the reliability of the measurements is unknown. Furthermore, the measurement of atrophy was based on comparison with the uninjured leg, assuming that the legs had equal muscle volume before the injury. A recent study reported between-limb differences in the muscle volume of the individual muscles in the triceps surae were small and non-significant (mean symmetry index: 0.4% ± 4.1)[(16)]. Furthermore, the uninjured leg was affected during the rehabilitation. Some studies argue that the uninjured leg undergoes hypertrophy due to increased workload and others that the uninjured leg undergoes hypotrophy due to general inactivity in the rehabilitation period[17,18]. The optimal assessment of atrophy would be a comparison with preinjury values, but as this is not possible, we consider the chosen method the best alternative.

Conclusions

Cross-sectional area measurement on a single MRI slice 26 cm proximal to the talus can be used as a surrogate for volumetric measurements (R^2 0.78) when investigating atrophy of the triceps surae muscle group after Achilles tendon rupture. However, this approach is not suitable when investigating the individual parts of the muscleusing.

Acknowledgements

The authors would like to thank statistician Thomas Kallemose (TK) for statistical guidance in planning and executing the analyses.

Author's contributions: Each author contributed individually and significantly to the development of this article: IH *(https://orcid.org/0009-0004-2119-5128) Conceived and planned the activities that led to the study, collected data, performed the statistical analysis, interpreted the results achieved, wrote the paper, participated in the reviewing process; ABO (https://orcid.org/0000-0002-2013-8045) Participated in planning the activities that led to the study, participated in the data collection, participated in the reviewing process; MSH *(https://orcid.org/0000-0003-4873-7055) Participated in planning the activities that led to the study, participated in the reviewing process; PH *(https://orcid.org/0000-0003-2098-0272) Planned the activities that led to the study; KWB *(https://orcid.org/0000-0003-2620-5891) Planned the activities that led to the study, interpreted the results achieved, approved the paper, participated in the reviewing process. All authors read and approved the final manuscript. *ORCID (Open Researcher and Contributor ID) iD.

References

1. Svensson RB, Couppé C, Agergaard A, Ohrhammar Josefsen C, Jensen MH, Barfod KW, et al. Persistent functional loss following ruptured Achilles tendon is associated with reduced gastrocnemius muscle fascicle length, elongated gastrocnemius and soleus tendon, and reduced muscle cross-sectional area. Transl Sport Med. 2019;2(6):316-24.
2. Heikkinen J, Lantto L, Piilonen J, Flinkkilä T, Ohtonen P, Siira P, et al. Tendon Length, Calf Muscle Atrophy, and Strength Deficit After Acute Achilles Tendon Rupture: Long-Term Follow-up of Patients in a Previous Study. J Bone Joint Surg Am. 2017;99(18):1509-15.
3. Leppilahti J, Lähde S, Forsman K, Kangas J, Kauranen K, Orava S. Relationship between calf muscle size and strength after achilles rupture repair. Foot Ankle Int. 2000;21(4):330-5.
4. Rebeccato A, Santini S, Salmaso G, Nogarin L. Repair of the achilles tendon rupture: a functional comparison of three surgical techniques. J Foot Ankle Surg. 2001;40(4):188-94.
5. Speedtsberg MB, Kastoft R, Barfod KW, Penny JØ, Bencke J. Gait Function and Postural Control 4.5 Years After Nonoperative Dynamic Treatment of Acute Achilles Tendon Ruptures. Orthop J Sports Med. 2019;7(6):2325967119854324.
6. Fukunaga T, Roy RR, Shellock FG, Hodgson JA, Day MK, Lee PL, et al. Physiological cross-sectional area of human leg muscles based on magnetic resonance imaging. J Orthop Res. 1992;10(6):926-34.
7. Pons C, Borotikar B, Garetier M, Burdin V, Salem D Ben, Lempereur M, et al. Quantifying skeletal muscle volume and shape in humans using MRI: A systematic review of validity and reliability. PLoS One. 2018;13(11):1-26.
8. Albracht K, Arampatzis A, Baltzopoulos V. Assessment of muscle volume and physiological cross-sectional area of the human triceps surae muscle in vivo. J Biomech. 2008; 41(10):2211-8.
9. Mersmann F, Bohm S, Schroll A, Arampatzis A. Validation of a simplified method for muscle volume assessment. J Biomech. 2014; 47(6):1348-52.
10. Vanmechelen IM, Shortland AP, Noble JJ. Lower limb muscle volume estimation from maximum crosssectional area and muscle length in cerebral palsy and typically developing individuals. Clin Biomech Bristol Avon. 2017; 51:40–4.
11. Belavý DL, Miokovic T, Rittweger J, Felsenberg D. Estimation of changes in volume of individual lowerlimb muscles using magnetic resonance imaging (during bed-rest). Physiol Meas. 2011;32(1):35-50.
12. Bossuyt PM, Reitsma JB, Bruns DE, Gatsonis CA, Glasziou PP, Irwig L, et al. STARD 2015: an updated list of essential items for reporting diagnostics accuracy studies. BMJ. 2015;351:h5527.
13. Hansen MS, Vestermark MT, Hölmich P, Kristensen MT, Barfod KW. Individualized treatment for acute Achilles tendon rupture based on the Copenhagen Achilles Rupture Treatment Algorithm (CARTA): A study protocol for a multicenter randomized controlled trial. Trials. 2020;21(1):1-14.
14. Hansen MS, Bencke J, Kristensen MT, Kallemose T, Hölmich P, Barfod KW. Achilles tendon gait dynamics after rupture: A three-armed randomized controlled trial comparing an individualized treatment algorithm vs. operative or non-operative treatment. Foot Ankle Surg. 2023;29(2):143-50.
15. Heikkinen J, Lantto I, Flinkkila T, Ohtonen P, Niinimaki J, Siira P, et al. Soleus Atrophy Is Common after the Nonsurgical Treatment of Acute Achilles Tendon Ruptures: A Randomized Clinical Trial Comparing Surgical and Nonsurgical Functional Treatments. Am J Sports Med. 2017;45(6):1395-404.
16. Rothwell DT, Williams DJ, Furlong LM. Measuring muscle size and symmetry in healthy adult males using a time-efficient analysis of magnetic resonance images. Physiol Meas. 2019;40(6):064005.
17. Benjaminse A, Holden S, Myer GD. ACL rupture is a single leg injury but a double leg problem: too much focus on 'symmetry' alone and that's not enough! Br J Sports Med. 2018;52(16):1029-30.
18. Barfod KW, Feller JA, Hartwig T, Devitt BM, Webster KE. Knee extensor strength and hop test performance following anterior cruciate ligament reconstruction. Knee. 2019;26(1):149-54.